CRANFIELD UNIVERSITY

EVAGGELOS LAVDAS

DEVELOPING A FRAMEWORK FOR IMPROVING THE QUALITY OF COST ESTIMATES

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DEVELOPING A FRAMEWORK FOR IMPROVING THE QUALITY OF COST ESTIMATES

Supervisor: Prof. R. ROY & Dr. C. WAINWRIGHT

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Abstract

Cost estimating is a knowledge intensive task, involving a high degree of subjectivity. Consequently, many of the current cost estimating (CE) processes lack formalisation, often resulting in the branding of cost estimating as a "part art, part science" discipline. This thesis is concerned with understanding the factors that influence the quality of the cost estimating process. The aim is to develop a framework that will improve the perceived quality of cost estimates, by minimising the subjectivity involved the current CE process.

A literature review examines the shortcomings of the current CE processes. It was identified that there is a lack of methodologies for eliciting CE knowledge, as well as mixed views across authors regarding the CE knowledge requirements. In addition, the review identifies that the current methods for assessing the quality of cost estimates are unstructured and highly subjective. By adopting a case study approach, the current CE processes across a number of organisations were captured, resulting in the identification of their weaknesses. A detailed study was carried out regarding the knowledge associated with the cost estimation of complex mechanical hardware products. This led to the development of a Knowledge Elicitation (KEL) methodology, tailored to the needs of cost estimators.

Through the use of a survey study, it was identified that the quality of a cost estimate is dependent on the fulfilment of a number of inherent characteristics. It was demonstrated that there was some variation in the relative contribution of each characteristic influencing the overall quality of the estimating process. These findings were implemented in a prototype software tool, which cost estimators could use to assess and quantify the quality of their estimates. A framework was developed based on the merge of the prototype tool and the KEL methodology. The framework's purpose is to aid cost estimators in acquiring all the necessary knowledge for developing cost estimates of good quality. Novice cost estimators will find the application of the framework particularly beneficial, since they lack the experience and knowledge in a particular domain.

In conclusion, it was demonstrated through the case studies that the use of the proposed framework provides novice cost estimators with a formalised process for developing cost estimates of quality similar to the one of experts. The framework was applied on case studies within the aerospace and automotive industry, and their results were validated by experts within the collaborating organisations. As a result of this study's findings, key areas for future research were identified. The adoption of this approach by cost practitioners could provide increased credibility to their work and a higher level of confidence in their cost estimates.

Acknowledgments

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There are a number of people who went beyond their duty in order to help me with this study. Especially I would like to acknowledge Mr. D. Kartalos and all his colleagues for providing me support during my research; as well as providing me with a good 'industrial' learning experience. On the subject of going beyond the line of duty, my most sincere acknowledgements go to D. Sauve for all his help both towards my study and on a professional level.

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On a personal level, there were a number of people which kept me sane and helped me on varying levels throughout this study. My acknowledgements go to Nikos, Nancy, Ina, George and my brother.

Finally, I would like to thank Roza, Pantelitsa and Alkis for their indirect support. Most importantly, I would like to thank my mother for all the support and sacrifices all these years.

End of my 'Oscars' Speech…

List of Publications

Lavdas E., Roy R. and Wainwright C., Identifying the key factors affecting the quality of a cost estimate, Leading the Web in Concurrent Engineering, Ghodous P., Dieng-Kuntz R and Loureiro G. (eds), 2006, 143: 737-745

Lavdas E., Roy R., Wainwright C. and Houseman O., Cost Estimating Knowledge Capture: A Novice Based Approach, ISPA/SCEA Conference Proceedings, 2005, Denver, USA

Houseman, O., Roy, R., Wainwright, C. and Lavdas, E., Cost-Estimating Aircraft Systems at a Conceptual Design Stage, Next Generation Concurrent Engineering, Sobolewski, M. and Ghodous, P. (Eds.), 2005, ISPE Inc., pp. 563-568

Houseman, O., Roy, R., Wainwright, C. and Lavdas, E., Cost Optimising Aircraft Systems at a Conceptual Design Stage, *International Journal of Manufacturing Technology and Management (IJMTM)*. Paper accepted for publication on December 2007

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List of Acronyms

ABC	Activity Based Costing
AoA	Analysis of Alternatives
BOE	Basis of Estimate
BOM	Bill of Materials
CAD	Computer Aided Design
CE	Cost Estimating
CEQA	Cost Estimate Quality Assessment (tool)
CBR	Case Based Reasoning
CER	Cost Estimating Relationship
DOE	Department of Energy (U.S.)
EACE	European Aerospace Cost Engineers (working group)
EJ	Expert Judgement
EPSRC	Engineering & Physical Sciences Research Council
FBC	Feature Based Costing
ICAM	Integrated Computer Aided Manufacturing
IDEF	Integration Definition Function Modelling
ISPA	International Society of Parametric Analysts
G&A	General & Administrative
KBS	Knowledge Based System
KC^2	Knowledge Capture for Cost (methodology)
KEL	Knowledge Elicitation
KEN	Knowledge = Expert - Novice
MOD	Ministry of Defence (UK)
NASA	National Aeronautics and Space Administration
NN	Neural Networks
OEM	Original Equipment Manufacturer
PBS	Product Breakdown Structure
PE	Parametric Estimating
PFG	Pricing & Forecasting Group (MOD)
RFP	Request for Proposal
RFQ	Request for Quote
ROM	Rough Order Magnitude
SCEA	The Society of Cost Estimating & Analysis
SME	Subject Matter Expert
SoW	Statement of Work
WBS	Work Breakdown Structure

"It is the mark of an instructed mind to rest satisfied with the degree of precision which the nature of the subject admits and not to seek exactness when only an approximation of the truth is possible"

Aristotle, 384 – 322 BC

Except where otherwise stated, this thesis is the result of my own research and does not include the outcome of work done in collaboration.

CHAPTER 1 – INTRODUCTION

The Society of Cost Estimating & Analysis (SCEA) defines cost estimating as "the art of approximating the probable cost or value of something based on information available at the time" (SCEA, 2007). The development of a cost estimate is a knowledge intensive process. In producing a cost estimate, the cost estimator taps into a vast amount of knowledge which has been developed through years of hands-on experience in a particular domain. Consequently, there is always a degree of subjectivity involved in this process. The following statement from the National Aeronautics & Space Administration (NASA) fully encapsulates the involvement of the subjective element into the cost estimating (CE) process:

> "Cost estimation is part science, part art. There are many well-defined processes within the cost estimating discipline. There is also a subjective element to cost estimating that makes the discipline an art" (NASA, 2004).

This mainly has to do with the subjective judgement involved, which is considered by Beltramo (1988) as acceptable; even desirable. Buxton *et al*. (1994) note that "for far too long cost estimating has been a black art, heavily dependent on experience, judgement and historical data". The 'art' aspect of the cost estimation has occurred due to the view that aspects of the current CE process lack of formalisation.

This lack of formalisation in some of the CE processes could result in the compromise of the perceived quality of cost estimates. The perceived quality of a cost estimate is linked to the attainment of quality in the CE process. Grant (2004) identified that the quality in the CE process, and the knowledge utilised by the cost estimator, will determine how good a cost estimate is.

In the past, a lot of effort and research initiatives were focusing on the methods and techniques of cost estimating, with little attention given to the more qualitative aspects of the discipline. As a result, the cost estimating community understands the importance of increasing the transparency to their discipline, through the application of formalised techniques and methodologies. This will contribute towards increasing transparency and adding credibility to their work; especially in areas that are surrounded by the use of subjective judgement.

In summary, this thesis is concerned with increasing the formalisation of these subjective-prone activities of the current CE process. As a result, a framework was developed that cost estimators can apply for producing a cost estimate of good quality. This is achieved through the provision of a systematic knowledge elicitation methodology, and a structured means for assessing and quantifying the quality of cost estimates. The latter was implemented within a software tool, which cost estimators can use to check the quality of their estimate, and identify areas of weaknesses.

There are a number of motivations for industry to implement the proposed framework within their current CE process, summarised as:

- Implement a structured approach for capturing CE knowledge during the development of a cost estimate.
- Accelerate the learning curve of novice cost estimators, by reducing their dependency on experts.
- Improve the quality of their cost estimates, firstly by having a means to check quality, and secondly by improving their estimating processes based on the lessons learnt.
- Increase the confidence and credibility in the cost estimates developed; thus, providing decision-makers with a quantifiable measure of estimate quality.
- As a result, that would increase the confidence in the negotiations with suppliers.
- In overall, increase the formalisation of the current CE processes.

In the following Section, a number of challenges associated with cost estimating are presented.

1.2 Cost Estimating Challenges

Cost estimates serve many purposes. They could be used for assessing a supplier's quote, pricing a product in response to a customer's Request for Quote (RFQ), carrying out feasibility studies, analysis of alternatives, to name a few. Submitting an accurate price to a customer is based on the identification of the probable costs that are going to be incurred by carrying out the proposed work. The increased competition in many industries, has led organisations to placing more importance on the determination of their costs.

Automotive companies always faced stiff competition in the market; and as a result their business model is based on a small profit margin between price and cost. In recent years, the aerospace industry seems to follow this trend since competition in many product ranges has increased. Curran *et al*. (2006) noted that "market pressures continue to force both companies and customers to demand aerospace products at reduced prices, resulting in the shift from *Price= Cost + Profit + Contingency*, to *Profit = Price – Total cost*". Underestimating the cost could result in loss of profit, while overestimating could result in a loss of potential sales due to introducing a non-competitive product to the market. Market forces cannot, in most cases, be controlled. Something else has to give away, in order to stay competitive; such as pricing a product competitively against the risk of reduced profit margins. Thus, it becomes absolutely crucial for an organisation to be aware of the exact cost of manufacturing a product. Figure 1.1 presents the fine balance between competitive pricing and ensuring that profits are realised.

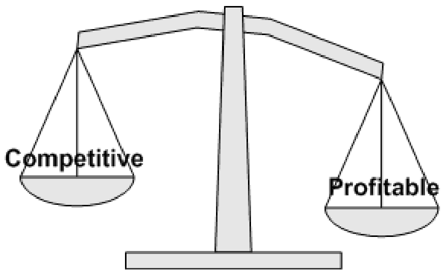


Figure 1.1 – The Balance between being Competitive and Profitable

Therefore, it is highly important that cost estimates are accurate, providing a concise picture of the costs associated with developing a product. There is a considerable effort by organisations to produce tools and formal methods that would increase the accuracy of cost estimates, so that business decisions can be made with increased confidence (Koonce *et al*., 2003). Norek and Pohlen (2001) highlight the importance of having knowledge about your costs in order to firstly be competitive and secondly be able to negotiate with other parties of the supply chain. As presented earlier, cost estimating is a knowledge intensive process, often involving many uncertainties. Akintoye & Ftizgerald (2000) identified that inaccuracy in cost estimates is often attributed to the lack of practical knowledge. The lack of knowledge could potentially compromise the quality of a cost estimate.

The review of cost estimates is currently an unstructured process, involving a high degree of subjectivity. A structured review process lacks all together in some organisations. Potential consequences can be: a) cost estimates do not achieve high quality standards, and b) cost estimators do not receive the necessary feedback, essential in improving their CE skills based on the lessons learned. One of the reasons for not having established review processes is the lack of understanding regarding the quality of cost estimates, and inherently of the quality in the CE process. The importance of having a structured cost estimate review process within every CE department in industry has been identified within literature (Dysert and Elliot, 2002).

Novice cost estimators are particularly prone to the aforementioned problems, since they lack both knowledge and experience in a new domain. In summary, the main problems faced by novice cost estimators are:

- Lack of knowledge regarding the domain.
- Experts are often busy. Thus, techniques and methods should aid novices in becoming less dependent on experts during the development of a cost estimate
- Limited time for developing a cost estimate due to the nature of a short CE lifecycle (Schehr, 1989).
- Lack of structured methods to follow while developing a cost estimate (Joumier, 2006); to guide, and aid, them through the various subjective-prone processes.
- Lack of experience in being able to judge whether their cost estimate is of good quality; and what its weaknesses are.

In the following Section, the context of this research study is presented.

1.2 Research Context

This study focuses on the cost estimation of complex mechanical hardware products. Mechanical hardware products would typically include structural entities, mechanical assemblies and mechanisms. The scope of the study in terms of the framework development focuses mainly on two industries; the aerospace and automotive. However, parts of the study, such as the investigation of quality into the current CE process, are intended to be more generally applicable.

Within the context of this thesis, the author regards knowledge as the domain knowledge, which a cost estimator needs to posses in order to produce a cost estimate for a product within that particular domain. This is the kind of knowledge which is developed through the accumulation of years of experience within a field, and it is often difficult to teach and pass onto new members entering that domain. Effectively, there is always a learning period associated with understanding that domain and developing the knowledge required. Thus, the knowledge of the CE practices, which could be described as the skills of cost estimators, was excluded from the context of this study since it could be acquired though training and/or qualifications.

1.3 The 'Cost-Expert' Project

This research was part of a larger EPSRC initiative, titled as 'Formalisation and Integration of Expert Judgement in Cost Engineering (Cost-Expert). Airbus (UK) and Galorath International Ltd. have been the main industrial sponsors of this project.

The overall aim of the research was to develop a formal representation of expert judgement in order to explicitly integrate it within the cost engineering process at the conceptual design stage As such that knowledge can be captured as a cost estimate is developed. The main drive behind this project was to increase the formalisation of the current cost estimating processes. The main focus of the project was the civil aerospace industry.

The overall objectives of the Cost-Expert project are:

- Identify the industrial requirements for formally integrating expert judgement within the cost estimating process
- Analyse the nature and extent of expert judgement use within the cost engineering process
- Analyse commercial tools for capability in knowledge capture and reuse
- Develop a library of standard templates to represent different categories of expert judgement
- Develop a novel framework to analyse the quantitative impact of an expert judgement on cost
- Develop and implement (a prototype) an integrated framework to represent expert judgement using the standard templates, perform impact analysis and integrate it within the existing cost estimating process.

Consequently, the focus of the study presented in this thesis emerged from a number of the objectives of the overall 'Cost-Expert' project, to some extent; and parts of this study's findings were utilised in order to partially fulfil some of the Cost-Expert project's objectives.

1.4 The Collaborating Organisations

Throughout the period of this research study the author collaborated with a number of organisations. The collaboration with three of them resulted in carrying out three case studies, where the proposed framework was applied on actual cost estimating scenarios. Being immersed in an industrial environment helped the researcher to understand both the overall subject, and also to generate new ideas after being subjected to inputs from experienced cost estimators within the field.

1.4.1 Hellenic Aerospace Industry

Hellenic Aerospace Industry (HAI) is a state-owned defence organisation located in Greece, with an extensive client base both in domestic and international markets. HAI is involved in a variety of activities delivering high quality services and products to both commercial and military customers. Activities as such include the maintenance and repair of military aircrafts and engines, the development and manufacturing of electronic, telecommunication and satellite systems, aero-structures manufacturing and assembly, training services on defence and aerospace industry skills and the co-development and co-production of weapon systems. World-wide, their clients represent a number of high calibre aerospace manufacturers such as Airbus, Boeing, Dassault Aviation, Pratt & Whitney, SNECMA, Raytheon, EADS and General Electric.

Cost estimating activities within HAI take place predominately within the 'Estimations & Feasibility Studies' department, part of the Finance directorate. Activities include the development of complete cost estimates in response to a customer's Request for Quote (RFQ), cost inputs to proposals development, pricing, economic investment analysis and feasibility studies. During the preparation of a cost estimate, inputs will be provided by many functions of the organisation such as Engineering (e.g. Production), Purchasing, to name a few. Figure 1.2 graphically presents a simple interaction diagram between the various departments, in preparing a response to a customer's RFQ.

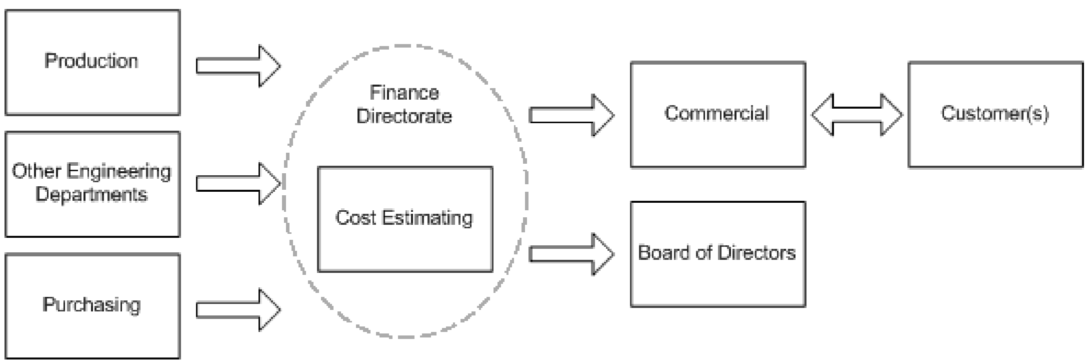


Figure 1.2 – An Overview of Stakeholders' Interactions in Producing a Cost Estimate

As a result, the development of cost estimates requires the co-ordinating inputs from a number of different departments, and more importantly the exchange of information between the Finance and Engineering functions of the business. The process depends on the inputs of experienced production planners. In addition, cost estimators have to obtain quotes both from sub-contractors and materials suppliers, when applicable.

1.4.2 Automotive Consultant

The author collaborated with an expert from the automotive sector, in one of the case studies presented within this thesis. The expert has a wide experience in cost estimating within the automotive industry, working for OEMs in the past, and currently providing his services on a consultation basis.

Part of his past responsibilities included the development of should-cost estimates for a variety of automotive parts. Estimates as such would be used (by an OEM) to set targets on the prices that the OEM is willing to pay to their suppliers. The cost estimates require a very good understanding of the engineering aspects in the part's development, as well as a good commercial understanding of the suppliers' rates and the way that a supplier derives a price in response to an OEM request for quote.

1.4.3 C.I. Consultants Ltd.

C.I. Consultants Ltd is a specialist business consultancy and training provider, primarily to the aerospace industry. CIC Ltd supports a variety of aerospace clients on the development and evaluation of proposals, assisting with the negotiation process, providing cost reduction through training and awareness, and the provision of cost and pricing modelling activities. Their core cost capabilities include the preparation of independent cost estimates, as well as the support on clients' cost modelling activities, pricing analysis, cash-flow modelling and industry benchmarking.

1.4.4 Airbus (UK)

Airbus is a leading aircraft manufacturer producing aircrafts in the ranges of 100 to more than 500 seats. Airbus had an annual turnover of approximately €26 billion euros in 2006. It currently has 57,000 employees and contributes to the global economy with design and manufacturing facilities in Germany, France, UK and Spain as well as through its subsidiaries in the USA, China and Japan.

Airbus UK is responsible for the design and manufacture of the wing structures for all Airbus aircraft models. In addition, it owns the design authority for both designing and supplying the fuel system for the Airbus product range. For a number of Airbus models, Airbus UK also designs and supplies complete landing gear systems. This in-house knowledge and experience has sustained Airbus UK as the leader in these business areas, within the overall organisation.

The 'Design to Cost & Value Analysis' department was directly involved in developing models and tools to aid decision makers within the business. The majority of such models were aimed at aiding decision-makers during the early phases of a project, with understanding the impact on costs that various design choices may potentially have. These models are knowledge based, driven by knowledge drawn through the vast expertise of design and manufacture that the organisation has accumulated throughout the years.

1.4.5 Galorath International Ltd.

Galorath began as a consulting firm in 1979, and during its course of growth it has aimed to provide the industry with a set of decision support and optimisation software tools. In particular, Galorath focuses on the development of commercial parametric tools, to help organisations derive costs of prospective projects/products during the early stage of their lifecycle. As result, Galorath is renowned within the cost estimating community for their SEER suite of parametric tools focusing on the cost estimation of a variety of technologies and products.

Galorath have acquired a large amount of experience in the area of cost estimating and they have contributed in the field through their software tools, consultation, as well as publications. Their consulting CE experience spans across a number of different industries.

1.5 Research Aim

Based on the challenges currently faced in the cost estimation of complex hardware mechanical products, and the overall research context, the aim of this thesis is:

> To develop a framework that will improve the perceived quality of cost estimates, by minimising the subjectivity involved in the CE process

In the following Section, the author presents the thesis structure, in order to familiarise the reader with the content of this study.

1.6 Thesis Structure

In the previous Section, the research aim was presented based on the research problem identified. In this Section, the author presents the structure of this thesis familiarising the reader with the work and the sequence of events leading to the fulfilment of the research aim.

In Chapter 2, the author presents a critical analysis of the literature related to the problem areas. The literature review findings are utilised in understanding the research gaps, and defining the research objectives for satisfying the overall aim of this study.

In Chapter 3, the objectives for fulfilling the overall research aim are defined, based on the findings from the literature review. Consequently, the development of the research methodology is presented. This was achieved following a careful analysis of the available approaches and strategies. The selection of an approach and strategy, in carrying out this study, was based on the nature of the research objectives and the available support to the researcher.

In Chapter 4, the author examines the knowledge requirements for the cost estimation of mechanical hardware products. In addition, the CE process is modelled following a number of interviews with cost estimators from industry. Weaknesses in the current CE process are highlighted in the AS-IS model, and areas for improvement are proposed.

In Chapter 5, a survey is carried out in order to identify the factors contributing to the quality of cost estimates. As a result of the findings, the author proposes a novel method for assessing and quantifying the quality of cost estimates, based on rating a number of characteristics related to the cost estimate development process. In Chapter 6, the author describes how the proposed method was implemented into a software tool. The Cost Estimate Quality Assessment (CEQA) tool was tested by cost estimators against actual cost estimates, and it was validated against their subjective perception.

In Chapter 7, the development of a Knowledge Elicitation (KEL) methodology is presented based on observations from Chapters 4 and 5. The KEL methodology was coupled with the CEQA tool in forming an overall framework. The framework is applied on a case study, within an aerospace organisation. In Chapter 8, the framework is applied on two additional case studies; the former within an aerospace organisation and the latter within an automotive one. The validation of the framework is presented following the results of the case studies.

Finally, in Chapter 9, the research findings are discussed with particular interest to the implications of their generalisability and applicability. The key research contributions are presented, along with the overall conclusions of the thesis demonstrating how the research objectives have been fulfilled.

CHAPTER 2- LITERATURE REVIEW

In Chapter 1, the author presented an introduction to the problem area and aim of this research study. The aim of this Chapter is to review the literature relating to the context and research areas relevant to this study. The literature review aims to highlight any research gaps in the current pool of knowledge, and as a result provide a focus to this study in terms of improving the understanding of those areas.

The diagram presented in Figure 2.1, depicts the focus of the literature review. The literature presented in this chapter is mainly divided into two main discipline areas. The first area is cost estimating and the second is knowledge elicitation.

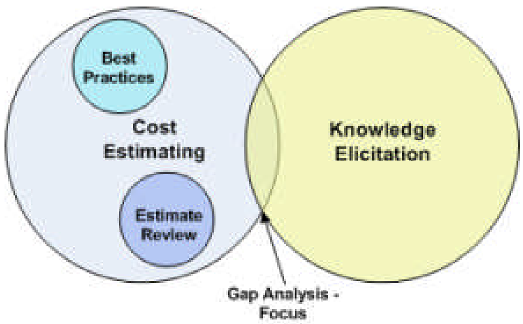


Figure 2.1 – Focus of Literature Review

In Section 2.1, an overview of cost estimating, available techniques and tools used is presented. Additionally, the purposes and typical uses of cost estimates are discussed. In Section 2.2, the author presents a number of practical issues concerning the use of cost estimating. An overview of the application of CE within the product lifecycle is provided. In addition, the skills of cost estimators as well as the variability in expertise are discussed. In Section 2.3, the current understanding of what contributes to good cost estimates, along with the current best practices, is presented. In addition, a review of current cost estimates review methods are presented highlighting their weaknesses.

In Section 2.4, the author introduces the reader to the concept of knowledge elicitation. The available methods are presented along with a critical review summary. In Section 2.5, current attempts in cost estimating knowledge capture are presented, with particular focus on existing methodologies for eliciting the required knowledge associated with developing a cost estimate. Finally, in Section 2.6, the key literature observations are summarised along with the identified gap areas in the current knowledge body.

2.1 Cost Estimating Overview

The first part of the literature review serves as an introduction to the domain of interest. It presents the discipline of Cost Estimating, by introducing the current cost estimating techniques found throughout literature and the relevant CE software. In addition, the typical purposes and uses of cost estimates are presented.

2.1.1 Introduction to Cost Estimating

The Society of Cost Estimating & Analysis (SCEA) defines cost estimating as:

> "*the art of approximating the probable cost or value of something, based on information available at the time*" (SCEA, 2007).

Due to the fact that a cost estimate is prepared for a product or service that is not yet produced/provided, during the development of an estimate there will be some unknown parameters. The estimator will have to apply his judgement and experience which has been gained over the years, in order to compensate for those uncertainties. Consequently, cost estimating is a subjective process that involves knowledge intensive tasks (Roy *et al.*, 2002) and subjectivity is an unavoidable passage whether complex cost models are constructed or simple spreadsheets (Rush & Roy, 2001).

'Traditional' cost estimates are often divided into two categories based on the level of detail of the estimate; 'rough' and detailed estimate (Roy, 2003). Further classifications have been devised based on the purpose and level of detail of an estimate, such as preliminary, semi-detailed and detailed estimates (Clark & Lorenzoni, 1978). Currently, a number of cost estimating techniques can be found in literature that are widely used within industry and the majority of them are well documented. Before presenting the CE techniques the author would like to introduce two principal approaches which are based on the way that cost estimates developed.

The first one is the 'Top-down' approach which it involves starting with the high-level definitions of a project and decomposing it into hierarchically lower functional elements for which costs could be sufficiently estimated. These kind of estimates are quick to develop and do not require a large amount of inputs. In contrast, the 'Bottom-up' approach is used when the cost estimator has a great amount of data related to the product that he/she wants to produce the estimate for. The process involves accounting of every detail relevant to the cost, from the smallest pieces of that project/product's functional decomposition, until reaching the higher level ones.

Based on the available cost estimating methods, other authors have recognised two main approaches: variant based and generative cost estimating (Weustink *et al.*, 2000; Watson *et al.*, 2006). According to Weustink *et al.* (2000) the variant based approach is based on "the similarity between the product under consideration and previously manufactured products" while the generative approach is based on "the fact that the costs of manufacturing a product depend on the required production operations". Determination of those operations will lead to the estimation of the cost of a particular product.

2.1.2 Cost Estimating Techniques

In this Section, the author presents a number of CE techniques, as identified in literature. Three of the most commonly used techniques include the analogical, parametric and detailed (or analytical) techniques.

Parametric

Parametric estimation is based on the use of Cost Estimating Relationships (CER). These are mathematical equations, which relate costs to one or more attributes of a product. For example, a correlation could be established that relates the cost of a turbine engine to the thrust that it generates. In order to develop a CER as such, known costs would have to be drawn against thrust values for a number of aircraft engines (example given in Figure 2.2, based on fictitious values). This means that one would need to have accurate historical data from previous projects that were similar with the current one, in terms of the product characteristics and/or technology.

The example presented shows a very simple linear equation constituting a CER, which could be used to estimate the cost of a future aircraft engine, based on the thrust that is going to produce. Based on the CER developed, one would get a

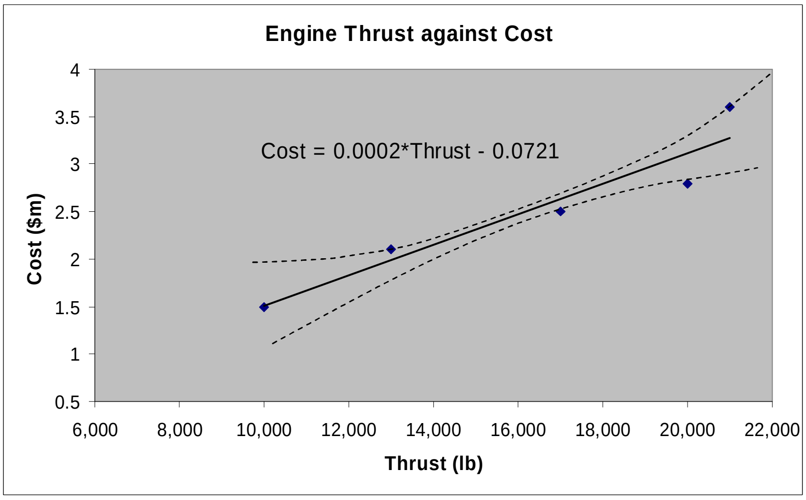


Figure 2.2 – A CER Relating the Cost of an Aircraft Engine in Relation to the Thrust Produced

'rough' cost value, which of course includes some inaccuracies to a certain extent. These are due to the linear regression that resulted in an optimal 'fit' line between the known points. In addition, if the new engine utilises new technological advancements, or it belongs to a different class of aircraft engines (for example military aircraft engines may have differences over their civil counterparts, both in cost and specifications), then producing an estimate using the above CER will incur a large error, as the equation does not take into account parameters such as design characteristics or engine family.

CERs can include lots of variables and be very complex. The approach has been well established and documented within literature (Hamaker, 1995; ISPA/SCEA, 2003). Due to the fact that it estimates cost based on very little known data about a product, their potential has been identified by industry and by CE software developers. A study of a leading aerospace manufacturer over a period of six years utilised 4,395 estimates and found that the average error between the estimated cost and the actual value was 7.1%; which it was more accurate than the traditional bottom-up approach (Daschbach & Apgar, 1988). In addition, it was found that inaccuracies in cost estimates dramatically declined after the first year of the study, due to the improved accuracy of the models, as a result of the continuous calibration and the learning curve effect on the estimators themselves.

Analogy Based Costing

The analogy-based cost estimating technique is based on the principle of using analogies between current and past cases for the purpose of estimating the cost of a new case. Past cases include historical information with known actual costs, which are stored in a database; it is often the case that a Case Based Reasoning (CBR) system is used for this purpose. A more explicit method, based on the analogy-based principle, is the 'pair-wise comparison'. The idea behind this technique is to estimate the size of "n" entities (entities could be cases, features or objects) by asking one or more experts to judge their relative size, instead of providing an absolute size value (Miranda, 2000). It requires the identification of a reference project that is similar to the project, which cost needs to be estimated, in order to carry out the paired comparisons. The comparisons are carried out by weighting how similar the two projects are, with methods such as the use of 'eigen-values' (Saaty, 1996).

Most of the research surrounding the use of the Analogy-based cost estimating method has taken place in the software domain. A software tool called ANGEL was developed at Bournemouth University, which utilises the Analogy-based method for the purposes of effort estimating (Shepperd, 2004).The analogy-based technique can be used whenever a product definition is available; however abstract it may be. It is used in the feasibility phase and mostly during the conceptual phase of the product lifecycle. However, this technique requires the implementation of an extensive database consisting of past products/projects (Farineau *et al.*, 2001).

Detailed Cost Estimating

Detailed cost estimating, as the word self-implies, is concerned with estimating the cost of a product based on all the operations and resources utilised in order to produce that product. For example the labour cost, materials cost, overhead costs and time to complete each operation is estimated for each part of that product and the final estimated cost will be the sum of all the costs associated with that product's parts. Stewart (1995) presents a detailed account as per the anatomy of a detailed cost estimate, along with the number of processes required to be undertaken to complete the process.

Detailed cost estimating produces very accurate estimates, but it requires a detailed definition of that product (Farineau *et al.*, 2001), as well as operation details and schedules. Due to that level of detail and the amount of information that the cost estimator would require, detailed cost estimates require a lot of time to develop. Layer *et al*. (2002) noted that the most accurate results can be achieved by the use of detailed models, using a bottom-up estimation approach to depict the product. However the use of this technique requires detailed and accurate data; which are often not available during the conceptual design stage, as Curran *et al*. (2003) has observed. Thus, it is often used during the later stages in the product lifecycle when more information, regarding the definition of the product and the intended production, is available.

Feature based Costing

Feature Based Costing (FBC) is another technique used for estimating the cost of a product. The logic behind the technique is to identify features associated with a product, and estimate the cost of the product based on its individual characteristics. For example, if a mechanical component has some holes or slots, these features are associated with additional manufacturing costs that will be incurred due to their existence. There are a number of researchers that have focused on the FBC technique for the purposes of cost estimating (Wierda, 1991; Zhang *et al.*, 1996; OuYang & Lin, 1997; Staub-French *et al.*, 2003; Souchoroukov, 2004). One of the main advantages of the FBC technique is that it allows designers to consider the implications that design decisions may have on the production and the lifecycle cost of the product (Brimson, 1998); thus making FBC very useful at the conceptual design phase of a product.

Although recent advances in the CAD software tools have been proved to be beneficial in terms of supporting the FBC technique, this link is still not fully established with respect to cost estimating. The reason lies on issues such as establishing what a feature may be and at what level of detail it should be defined. There is not a widely accepted methodology or standardised process across industry for defining the features of a product. Thus, it is left to the user(s) of this technique to decide on how to implement the technique for producing cost estimates.

Activity Based Cost Estimating

Activity Based Costing (ABC) is a product costing technique where initially costs are assigned on the specific activities of an organisation. The idea behind ABC is that for a particular product an amount of each activity, which is utilised by that product, could be attributed to that product. As a result, ABC requires the identification of the cost of all the activities within an organisation, so these relative activity costs could be assigned to the product afterwards. Due to the nature of the ABC technique there have been attempts where the activities were associated to specific manufacturing characteristics of a product, thus providing a form of "activity-based planning" (Boons, 1998). The ABC technique follows similar processes with the detailed estimating technique and requires a very good understanding of the product and the related activities, by the cost estimator; thus making ABC inappropriate for costing a product at the conceptual phase of its lifecycle (Roy, 2003).

In addition to the techniques presented, other methods could be utilised for cost estimation such as the implementation of fuzzy logic and neural networks (Zhang *et al.*, 1996). Concerns exist that the calculations within them is of a 'black-box' nature (Roy, 2003), thus making them less desirable for use by cost practitioners. A study carried out by Wang and Stockton (2001) examined the accuracy of artificial neural network structures under varying conditions, and concluded that the accuracy of the result depends on factors such as the number of layers and the number of processing elements per layer.

2.1.3 Cost Estimating Software Tools

There is a variety of software tools which can be used to develop cost estimates. A number of them are based on the parametric approach. Their main benefit is to provide cost estimators with a 'rough' estimate, at a time that they do not yet have a lot of knowledge defined about a new product. Hence, these kinds of cost models are found invaluable at the early conceptual design stage of a new product development.

Three commercial cost estimating software were reviewed. They were selected based on: a) available resources to the author at the time, and, b) because they are the leading software in the market, quite popular in terms of use within the cost estimating community.

SEER

Galorath Inc. (2004) develops cost estimating software products based on the parametric approach, which cover a wide of applications. SEER H and SEER DFM are used to cost hardware products. In addition to the hardware models, there are similar ones directed towards costing software and electronics products. SEER models can be used to develop estimates for a product based on whole lifecycle costs and they have the capability to produce detailed reports and analyses that could include risk and comparison of alternatives. SEER software incorporates a notepad function where the user(s) can write down notes regarding the rationale for assigning a set of values, or any other additional information.

PRICE

Price Systems (2004) also provide a suite of cost estimating software tools, based on the parametric approach. PRICE H is used to estimate hardware products and PRICE HL can be used as a supplementary tool to PRICE H for estimating the lifecycle costs of a product. PRICE software tool incorporates a free-text notepad function to capture assumptions made by the estimator, as the estimate is produced. However, similar to SEER's notepad function, the process of filling it out is not formalised and its use depends on the cost estimator. PRICE Systems have also developed the Knowledge-Manager which is a web-based tool that enables collaborative management of PRICE cost and technical data across teams and organisations. The tool provides a unified storage, retrieval, and analysis centre for PRICE software and hardware estimating data, and cost driver data. Knowledge-Manager supports the capture of the rationale of the assumptions made; it provides the means to compare estimates to existing benchmark data and to develop estimates by analogy to past projects.

ECM

ECM is developed by Cognition (2004) and consists of a central repository where all the sources of data that are needed in order to produce an estimate, are linked to. Similar to the PRICE Knowledge-Manager, it has the capability of capturing and storing estimates with attached assumptions that were developed by the user. This applies only at an estimate level and as a result the capability of storing knowledge related to lower product levels of that estimate is limited. ECM provides traceability for the estimates that are stored, where the user(s) may interrogate the cost data to identify the reasons regarding the make-up of particular cost elements.

In this Section, three leading cost estimating software tools were presented. In Section 2.5.2, these tools are further reviewed by the author, with particular focus on their potential capability towards the capture of CE knowledge.

2.1.4 Typical Purpose and Use of a Cost Estimate

The development of cost estimates within an organization may serve various purposes. Cost estimates may be developed for the purpose of budget activities, bidding, negotiations, investment analysis and other cost engineering and management activities (such as value analysis, defining a baseline in Earned Value Management, to name a few). Consequently, the purpose of a cost estimate could dictate both the techniques and processes which would be followed in developing that estimate, as well as the expected accuracy and effort that is going to be spent on producing that estimate.

Laderer and Prasad (2000) list several uses of a cost estimate such as: 1) audit project success, 2) control or monitor project implementation, 3) evaluate project estimators and developers, 4) quote the charges to users for projects, 5) schedule projects, proposed projects selection and 6) staff projects. Although their work is based on software development projects, the basic concepts are similar to other industries as well.

A common activity of many suppliers, within industries such as the aerospace and automotive, is the submission of proposals in response to customer Requests for Quotes (RFQ). An integral and crucial part of this process is the accurate estimation of how much the product/service is going to cost the company to produce/provide it. Setting a price for that product relies on the assumption that a reliable and accurate cost estimate was developed.

Other uses of cost estimating could be in the analysis of alternatives (AoA), where the cost of different options is estimated for the purposes of business decisions. In addition, cost estimates form the basis for any financial activities, such as the execution of investment analysis.

2.2 Practical Issues in Cost Estimating

In this Section, the author reviews some of the practical issues of cost estimating, relevant to the overall study. The use of cost estimating across the product lifecycle is examined, as well as the data and information requirements for developing cost estimates. In addition, the author investigates the difference in expertise between cost estimators, and how it affects their output, as well as the skills necessary in carrying out their job.

2.2.1 CE across the Product Lifecycle

There are some practical limitations regarding the application of the CE techniques in the different phases of the product lifecycle. The majority of them are a result of the lack of data definition (and current knowledge) available for a specific product, at the time that the cost estimate is developed. For example, when a new product is at the beginning of the conceptual design stage, and it is not very similar with other products produced in the past, then the use of the more detailed estimating techniques becomes limited. This is attributed to the lack of an accurate product definition, commercial knowledge and other engineering data that will not be available at that point to the cost estimator.

NASA (2004) summarises the factors which influence the selection of a cost estimating technique as being data availability, available schedule and resources, phase and maturity of a program and expectations. In effect all these criteria could be linked to a particular phase of a product's lifecycle. Table 2.1 presents the applicability of different cost estimating techniques across a product's lifecycle (Rush & Roy, 2000).

Table 2.1 – Cost Estimating Techniques and Product Lifecycle (Rush & Roy, 2000)

Cost Estimating Techniques	**PE**	**NN**	**CBR**	**FBC**	**Detailed Cost Estimation**
Used when					
Concept design phase (innovation)	√	x	√	√	x
Concept design (similar product)	√	√	√	√	x
Feasibility studies	√	√	√	√	x
Project definition	√	√	√	√	x
Full scale development	x	x	x	√	√
Production	x	x	x	√	√

The use of statistical or analogous models for cost estimation heavily relies on the use of historic data and as a result innovative technologies or new resources cannot be added (Layer, 2002). In contrast, such techniques are highly suitable for estimates regarding products for which historical data exist. In the case of new products, the use of more detailed techniques can take into account the particular individualities. In addition, as presented earlier in this thesis, the final selection of the CE technique also depends on the intended estimate purpose (and thus, the degree of accuracy and confidence expected, as a result of developing the cost estimate).

A supplier's responsibility typically ends with the delivery of the product; unless of course there are any special contractual agreements between the supplier and the customer(s) regarding lifecycle support, training, disposal or any other activities. Considering the whole product lifecycle in terms of cost, even during the early design stages, is very important at imparting and improving design and business decisions at an early stage. Many techniques and methods exist for lifecycle costing including Durarairaj's *et al*. (2002) who propose a life cycle cost analysis methodology which could be used to evaluate eco-costs, for developing a cost effective eco-design of a product.

2.2.2 CE Knowledge Requirements

In the previous Section, the author presented the various CE methods that are used for costing a product/service throughout the product lifecycle. It was presented that each CE technique requires a different amount of data and information (at hand) in order to estimate the cost of a product. Similarly, the level of knowledge varies according to both the CE technique applied and the phase in the product lifecycle. Roy *et al*. (2002) observed that one of the primary tasks of a cost estimator is to capture information and engineering knowledge; which in turn will be utilised for developing their estimates. The quality of cost information utilised is very significant towards achieving estimate accuracy (Oberlender and Trost, 2001).

Paramount to cost estimating, irrespectively of the technique used, is the availability and utilisation of data required to develop a cost estimate. NASA (2004) identified three main types of data and possible sources that will be needed in order to carry out an estimate, namely: cost, technical/operational and project data. Figure 2.3 lists some of the essential information that a cost estimator needs to obtain, in order to develop an estimate.

Souchoroukov *et al*. (2002) examined the data and information in cost estimating. In particular, Souchoroukov's (2004) study focused on the data and information requirements for cost estimation within an automotive industry environment. His study led to the development of a data infrastructure, which summarises and exhibits information about the data requirements, in the form of a web portal.

OuYang and Lin (1997) state that having accurate data is a critical factor for successfully implementing a cost estimation system. In fact many have come to

Data Category	Three Principal Types of Data	
	Data Type	**Data Sources**
Cost Data	Historical Costs Labor Costs CERs from previous projects	Basic Accounting Records Cost Reports Historical Databases Contracts (Secondary) Cost Proposals (Secondary)
Technical / Operational Data	Physical Characteristics Performance Characteristics Performance Metrics Technology Descriptors Major Design Changes Operational Environment	Functional Specialist Technical Databases Engineering Specifications Engineering Drawings Performance / Functional Specifications End User and Operators
Project Data	Development and Production Schedules Quantities Produced Production Rates Equivalent Units Breaks in Production Significant Design Changes Anomalies (e.g., strikes, national disasters, etc.)	Project Database Functional Organizations Project Management Plan Major Subcontractors

Figure 2.3 – Typical Data Types and Sources (NASA, 2004)

realise the importance of the cost estimator having the necessary knowledge regarding a particular product/project, leading to a common saying amongst practitioners that 'your estimate is as good as the data and information used to develop the estimate'. However, in many industries, commercial cost information are closely guarded by both manufacturers and government, as observed by Beltramo (1988); thus hindering even further the quest of cost estimators in capturing data required for completing their task.

Fong *et al*. (1998) observed that cost estimating is a multi-disciplinary profession. Similar observations were made by other authors too, where a cost estimator is viewed as a professional possessing multi-disciplinary skills and knowledge (Hamaker, 2000; Rush & Roy, 2001). In overall, cost estimating is a knowledge intensive task (Roy *et al*., 2002).

It is a cost estimator's responsibility to understand and validate the knowledge base used to develop estimates (NASA, 2004). Estimators may not have the necessary knowledge, and/or understanding, which is essential towards developing a cost estimate for a particular product/project. Common practice amongst cost estimators is to consult and seek advice from subject matter experts (SMEs); such as engineers, designers, project managers, and so on.

Mishra *et al*. (2002) studied areas within the costing profession which require training, and as a result identified ten knowledge types relating to engineering and commercial cost estimating activities. These include knowledge about the process, supplier, risk, material, costing process, product, company strategy, design, market trend and contact knowledge. The identified types represent a mix of domain knowledge and knowledge regarding the CE process, since the focus of their study was on the training requirements of cost estimators.

Accounts regarding the knowledge needed by a cost estimator, in order to produce a cost estimate, can be found in the construction industry domain (Stevens, 1995; Uppal, 2002). Throughout the literature there are various references listing the kinds of information that a cost estimator would need to have available, in order to carry out a particular type of estimate (Lovett, 1995; Humphreys & Wellman, 1996; Uppal, 2002). However, most of these studies are directed towards specific engineering domains, such as general manufacturing and construction. In addition, they are quite generic in terms of their context in these industrial domains.

A survey carried out within the construction industry revealed inaccuracies of the estimates that are produced could be accounted to the lack of practical knowledge of the construction process by those responsible to produce the cost estimates (Akintoye & Fitzgerald, 2000). The results of the survey also highlighted the specific types of knowledge that cost estimators feel they lack when faced with the task of preparing an estimate. Buxton *et al*. (1994) noted that the lack of detail in the original specification is one of the biggest problems to overcome, along with insufficient time to assess and estimate the cost of design alternatives.

Blackwell (2003) identified the types of knowledge that are used for the development of cost estimates within the Pricing and Forecasting Group (PFG) within the UK Ministry of Defence (MOD). Cost estimating knowledge within PFG could be categorised into three domains; defence equipment, industrial/manufacturing and pricing conditions. His findings are presented in Table 2.2.

Table 2.2 – Types of Knowledge within PFG's Costing Activities (Blackwell, 2003)

Types of Knowledge	
Engineering	**Pricing**
Contractor Processes	Contractor Capabilities
Defence Technology	Level of Detail (of estimate)
History	Make and Buy plan
Industry Trends	Pricing Risk
Materials	Requirement (of pricing)
Tooling	Supply Chain
	Type of Contract
	Type of Work

Typical sources of information available to a cost estimator include the Request for Quotation (RFQ), statement of Work (SoW), contract terms and conditions, federal regulations and referenced standards (Schehr, 1989). Souchoroukov (2004) also identified a list of potential sources for acquiring data and information regarding the development of cost estimates within an automotive industry setting. Hamilton and Westney (2002) suggest that the source of cost estimating data is as important as a best practice in itself.

In summary, it was identified that cost estimating is a knowledge intensive task and the quality of that knowledge has an impact on the result of the estimate. Within literature there a number of sources regarding the types of CE knowledge, mainly focusing on the data and information requirements, and being specific to particular domains and/or industries. In addition, the author observed that many accounts seem to include within cost estimating knowledge, the knowledge regarding the process of carrying out a cost estimate; essentially, related to the CE skills required for developing a cost estimate.

2.2.3 Skills of a Cost Estimator

In this section, the author presents references identified in the applicable literature regarding the skills of a cost estimator. Blanchard & Thacker (2007) define skills as "the capacities needed to perform a set of tasks that are developed as a result of training and experience". They differentiate between knowledge and skills, with the former being a prerequisite for learning skills while the latter being the proficiency of doing something; not just knowing how to do it. They further suggest that skills are developed as a result of training and experience.

The multi-disciplinary nature of the cost estimating profession, in terms of both skills and knowledge, could be best described by Hamaker (2000). His findings are presented in Figure 2.4.

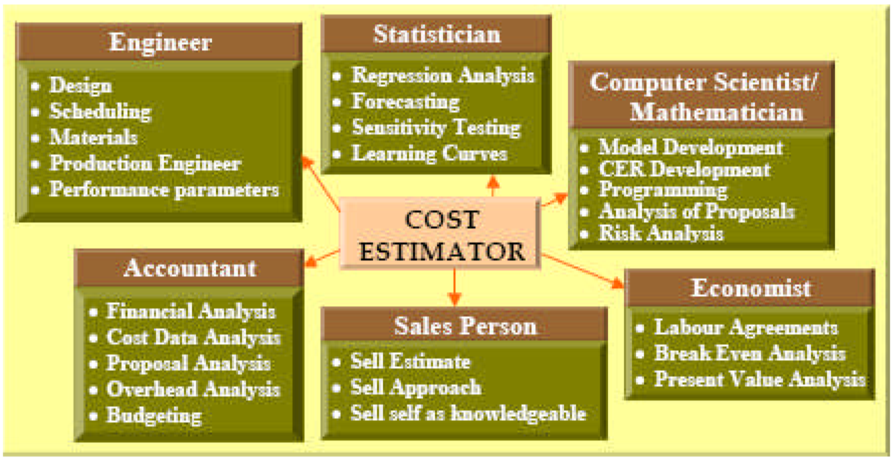


Figure 2.4 – Skills and Knowledge of a Cost Estimator (Hamaker, 2000)

A number of professional bodies and associations (in the area of cost estimating) have defined the skills that cost estimators should have; and consequently, the corresponding training requirements. Grant (2004) carried out a detailed study analysing all these points of references, in an effort to summarise the skills and competences associated with hardware cost estimating. Figure 2.5 presents his findings regarding the skills of a cost engineer.

Skill Clusters	Number of Skills
Core Skills and Competences	
Cost Estimating	32
Supporting Skills and Competences	
Manufacturing and Engineering	9
Project Management	12
Commercial Awareness	12
Financial & Accounting	15
Industrial Engineering	7
Business Awareness	21
Inter-Personal	15
Improvement Activities	9

Figure 2.5 – Set of Clusters Defining the Skills of a Cost Engineer (Grant, 2004)

Based on Grant's (2004) study, the set of skills identified particularly to cost estimating mainly focus on the cost estimating process itself. A number of these skills relevant to cost estimating are: "Carry out complex cost estimating using several or all of the methods of estimating", "Derive and use complex cost estimating relationships", "Design, develop and use appropriate cost models, including conducting sensitivity analysis", "Collect relevant and useful data in the available timescales" and "Define and cost risks, evaluate and analyse risks using appropriate tools and techniques and establish cost ranges" (Grant, 2004).

Cost estimators require a technical understanding of the domain where the cost estimate take place (Babcock, 2003). Knowledge and skills regarding the cost estimating practices are not enough. Cost estimators also need to have a good understanding of the engineering underpinnings of the product/project they base their estimate on; as well as a wider commercial and management viewpoint. Such a technical understanding is mainly acquired through experience gained in that particular domain, often supplemented by qualifications.

2.2.4 Expertise and its Implications to Cost Estimating

Casakin and Goldschimdt (1999) suggest that expertise in any domain consists of a combination of knowledge and skill. They also add that differences found in skill between novices and experts could be attributed to differences in their representation of knowledge. A similar view is shared by Hoffman (1998).

The difference of individuals in terms of expertise was studied by Dreyfus and Dreyfus (1986). As a result, they developed the *Dreyfus model* which describes individuals' expertise based on five categorisations: 1) Novice, 2) Advanced Beginner, 3) Competent, 4) Proficient, and, 5) Expert. A fundamental difference between a Novice and an Expert is that a novice needs to follow rules and guidelines, while the expert does not have to; s/he knows exactly what to do, based on "a vast repertoire of situational discriminations" (Dreyfus and Dreyfus, 2005). In addition, a novice lacks discretionary judgment; in contrast, an expert has a deep tacit understanding and intuitive grasp of situations.

The use of expert judgement in cost estimating, in the case of software estimating, is a significant part of the cost estimating process and is based on intuition (Jorgensen, 2004). The ability to apply sound and logical judgement relates to the experience of individuals, gained over years of involvement in a particular domain; and thus the development of both their knowledge and skills relating to that domain. Serpell (2005), is in agreement, suggesting that CE expertise consists of ability, competence, aptitude, experience, knowledge and familiarity. He further adds that the acquisition of cost estimating expertise is a learning process.

Beltramo (1988) highlights the importance of not just utilising data but involving also human judgement in the process. He adds that empirical data alone may be very misleading, since other issues affect costs that may not be initially apparent (such as competitive pricing). This observation is in agreement with Akintoye & Fitzgerald's (2000) findings where they found a link between cost estimate inaccuracy and lack of practical knowledge from the part of cost estimators.

Schehr (1989) observed that cost estimators often rely on engineers and other experts for the development of 'hardware descriptions', since they lack the all important technical knowledge. He emphasises the need for CE departments to develop people and procedures which will enable this transfer of knowledge from the various engineering functions of the business.

2.3 The Anatomy of a Good Cost Estimate

Developing a good cost estimate is the ultimate objective of a cost estimator. In this Section, the author presents some views from the literature regarding the current beliefs on what is a good, or bad, cost estimate.

2.3.1 Beliefs on what Constitutes a Good Cost Estimate

NASA (2004), within their cost estimating handbook, identified seven key areas which it is suggested that an estimate should fulfil. These are traceability, reasonableness, soundness, verification, validity, accuracy/consistency and completeness. It was also suggested that producing a good cost estimate is an iterative process (NASA, 2004).

Credibility, and in general acceptance by peers, is something that is also mentioned in the work of Grant (2004) as a trait of a good cost estimate. He suggests that "the quality of the estimating process and the skill and knowledge employed by the estimator, both in thought and documentation, will determine how good or bad an estimate is" (Grant, 2004). Boeschoten's (2005) work focuses on two main issues of a good cost estimate: reliability and accuracy. He adds that it is difficult to reach a consensus on what is a reliable or accurate estimate, as each cost engineer has their own ideas on the subject.

Akintoye and Fitzgerald (2000) carried out a survey regarding the CE practices in the UK construction industry. Some of the causes identified, resulting in estimate inaccuracies, are insufficient time to complete the estimate, poor tender documentation, lack of understanding of the project requirements, poor team communication and poor feedback on previous estimates' accuracy.

Following on Grant's (2004) comment regarding the quality of the CE process, the author wanted to explore the meaning of quality. The Merriam-Webster dictionary (2006) associate quality with the satisfaction of/to "a degree of excellence". The American Society for Quality define quality as the "the characteristics of a product or service that bear on its ability to satisfy stated or implied needs" (ASQ, 2006). The definition of quality that is widely used in industry, and which was adopted for the purposes of this study, is presented within the US version of ISO-9000 (ISO-9000, 2000). Subsequently, quality is defined as the:

> "…*degree to which a set of inherent characteristic fulfils requirements*"
>
> (ISO 9000:2000)

Thus, it is important to identify those *inherent characteristics*, which contribute towards achieving a cost estimate of good quality. Finally, the elements of good cost estimates could be best described by the current best practices found within literature. The following Section, aims to present those practices and identify the key ingredients of good cost estimates.

2.3.2 CE Best Practices

Similarly to many other disciplines, producing an output of good quality could be augmented by the use of industry best practices. In this Section, the author presents some views on the current cost estimating best practices, with particular focus to quality within the CE process. The application of best practices, and procedures, could potentially result in the formalisation of the overall process.

Hamilton and Westney (2002) identified 10 areas of best practices regarding the development of a cost estimate. Areas as such include: 1) definition of the scope of work, 2) definition of the project execution basis, 3) determination of estimating data and methods to be used, 4) assignment of qualified estimating resources, 5) calculation of cost of major elements, 6) estimation of scope of design, project management, start-up and owner costs, 7) establishment of exchange rates and escalation of future costs, 8) contingency to be applied, 9) overall estimate reasonableness checks, and, 10) comparison of costs with similar projects. These areas of investigation could be further analysed in order to review the relative quality of a cost estimate (Hamilton and Westney, 2002).

Similar areas of best practices were identified by Lavignia (2004). Both Lavignia's (2004) and Hamilton and Westney's (2002) studies focus on the construction industry; however some of the best practices mentioned are common across cost estimating activities, irrespectively of industry type.

The Society of Cost Estimating and Analysis (SCEA) within their Body of Knowledge Training material they refer to the characteristics of high quality cost estimates. Characteristics as such include accuracy, comprehensiveness, auditability, traceability, credibility and timeliness (SCEA, 2003). They raise concerns over the quality of cost estimates, due to inadequate documentation, the existence of tacit knowledge and the definition of 'good' data.

2.3.3 Pitfalls of Current CE Practices

As presented in Section 2.1.4, the use of cost estimating can serve various purposes and the selection of a particular CE technique is partially influenced by the stage in the product lifecycle. Although cost estimation can be used for the purposes of feasibility studies, design-to-cost and analysis of alternatives, where it becomes highly beneficial in industry is in the case of pricing activities, bidding, negotiations and budget activities. Activities as such highly impart on business decisions made and are explicitly related to making sure that the organisation will be profitable. As a result, decision-makers require a high degree of accuracy and certainty regarding the cost estimate they are presented with. The use of detailed bottom-up estimating technique, or often referred to as analytical, to develop the cost estimate is the choice of method when accuracy expectations are high.

However, accuracy comes at a cost, requiring an increased effort by the cost estimating teams. Larsen (1994) demonstrated that the cost of producing cost estimates increases as the estimate accuracy increases. Therefore, it is expected that detailed estimates should be as good as possible, first time. Samid (2003) noted that inaccuracy is generated due "to the lack of knowledge that is going to be realised when a project ends; but is unsuspected at the time of the estimate" (Samid, 2003). Lack of practical knowledge, by the part of the cost estimator, was found to be one of the most important reasons for inaccuracies found in cost estimates (Akintoye and Fitzgerald, 2000).

During the development of a cost estimate, an estimator would typically require inputs from engineers, designers and other commercial personnel. However, experts are busy and their time is invaluable. In addition, acquiring and maintaining knowledge from the process planners is an extremely expensive process (Layer *et al.*, 2002). The effort in acquiring all the necessary information and in developing an understanding of the product for which the estimate is produced for, could potentially be more than the effort required to actually do the cost estimate. Consequently, the effort of the knowledge elicitation activities is going to increase when a cost estimator is lacking any practical knowledge about the product/project. This problem becomes more acute in the case of junior cost estimators.

A study carried out by Kingsman & de Souza (1997) identified some possible sources of errors in the CE process. Errors as such could be attributed to the reliability of the information provided by the client, time pressure, dependency on others' estimations and not recognising the limitations of the experience with similar product activities, to mention a few.

Joumier (2006) noted that mechanisms regarding the CE processes have been, in some cases, unstructured. He emphasises the need for providing cost estimators with a framework; as a result of which, problems of under (or over) estimating could be avoided. The need for formalisation of many of the cost estimating processes is an issue often raised by cost researchers. Kingsman and de Souza (1997) highlighted that "currently cost estimating and pricing is a very unstructured decision-making process". This lack of formalisation across some of the CE processes is also emphasised by Rush (2002) within his findings, where he observed that experts make a number of judgements and decisions during the estimating process, which are often not captured.

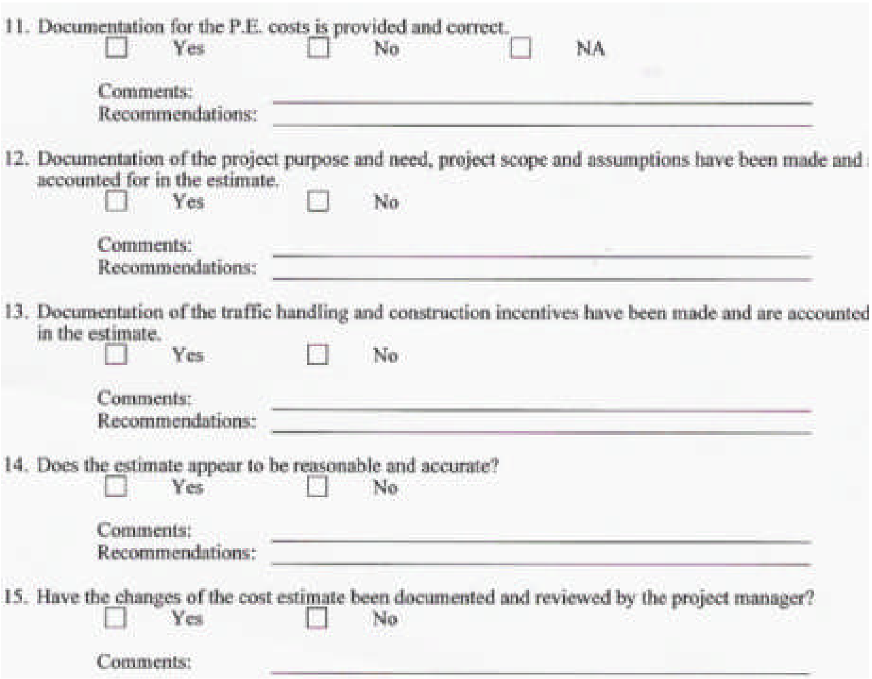
2.3.4 Current Initiatives for Reviewing Cost Estimates

Following the completion of a cost estimate, a number of actions need to be undertaken to ensure that the estimate is good and meets expectations. Dysert and Elliott (2002) highlight the need for a review and note that "a structured estimate review process should be a standard practice for all estimating departments". Leo and Knotowicz (2005) agree with this view, and add that a formal review process as such is going to ensure an estimate's quality, accuracy, completeness and consistency. The use of structured review techniques will guarantee that quality estimates are developed which will effectively support decision makers (Dysert and Elliott, 2002).

The use of checklists is employed by many organisations, as a means to assess and validate a cost estimate upon completion. Jorgensen (2004) noted that there is evidence in other fields that the use of checklists can bring novices up to a level similar to that of an expert. He used an example of a study carried out by Getty *et al*. (1988), where the performance of general radiologists was brought up to that of mammographers, through the use of a checklist. A reviewer would go through a cost estimate and note whether the requirements (in the checklist) have been satisfied, or not, and make any observations or comments regarding the cost estimate in general. Typical checklists consist of a set of questions. The reviewer, or the cost estimator, would have to review the estimate based upon those questions. The reviewer typically goes through those questions by replying yes or no and noting down any comments.

A drawback of establishing a thorough estimate review process is that it is time consuming and it is often the case that the amount of time allocated for an estimate review is short (Dysert and Elliott, 2002). In industry, peers or the manager check an estimator's work and make sure that the assumptions made and the data utilised are sound and reasonable. Formal estimate reviews are usually reserved for high value projects/programmes, and/or when the customer requires it; since the potential implications of estimating errors could be disastrous to an organisation. Another disadvantage of the cost estimate review process is that the whole review relies on the reviewer's intuitive judgement and experience, and the final result is usually not of quantitative nature. Thus, it is difficult to articulate perceptions, and enable stakeholders in that project/programme to comprehended objectively the results of the review activity.

There are limited published references regarding the availability of checklists for the purposes of cost estimate review. An example of a checklist as such is provided by the Missouri Department of Transportation, referred to as project estimate quality assurance report form. An extract of this form is presented in Figure 2.6, demonstrating some exemplar fields that a reviewer would have to fill during an estimate assessment.



11. Documentation for the P.E. costs is provided and correct.
☐ Yes ☐ No ☐ NA
Comments:
Recommendations:

12. Documentation of the project purpose and need, project scope and assumptions have been made and accounted for in the estimate.
☐ Yes ☐ No
Comments:
Recommendations:

13. Documentation of the traffic handling and construction incentives have been made and are accounted in the estimate.
☐ Yes ☐ No
Comments:
Recommendations:

14. Does the estimate appear to be reasonable and accurate?
☐ Yes ☐ No
Comments:
Recommendations:

15. Have the changes of the cost estimate been documented and reviewed by the project manager?
☐ Yes ☐ No
Comments:

Figure 2.6 – Extract from a Typical Checklist Used for Cost Estimates Review (MoDOT, 2007)

Checklists similar to the one exhibited in Figure 2.6 have also been developed by the U.S. Department of Energy (1997) and the Nuclear Decommissioning Authority (2006), both of which follow a similar format of reviewing an estimate based on a set of pre-defined fields. The end result of this review process will typically be a decision on whether the estimate is credible enough, and/or recommendations for improvement.

Boeschoten (2005) proposed a rating system for improving the reliability of an estimate, conceptually similar to checklists such as the ones presented above. Since he proposes that estimate reliability is largely associated with changes incurred in the scope of a project (throughout its lifecycle), he defined a number of drivers that may change the project's scope. He adds that this rating instrument could be useful in "determining the quality of a scope and the ensuing estimate" (Boeschoten, 2005).

Oberlender & Trost (2001) developed an estimate scoring procedure for predicting the accuracy of early cost estimates, which is based on 45 key elements of a cost estimate. These elements were defined by their research team and some of them are specific to construction industry projects (elements such as 'plot plan', 'environmental assessment', 'logistics', to name a few). Data were then collected, through the use of a questionnaire, regarding the elements' rating scores and specific project cost information. Their study resulted in a method that could be used for predicting estimate accuracy, based on the rating process of the 45 elements.

The majority of the methods reviewed so far rely on the same concept of checking the estimate qualitatively against a number of pre-defined points. The author feels that although these methods could be beneficial in a review process, they are highly subjective and do not provide a quantitative measure (as a result of the review process), which it could be related to some common understanding regarding how good an estimate is.

The only method which minimises the subjectivity involved, compared to the rest of the methods, is the one proposed by Oberlender & Trost (2001). However, after careful review, it was identified that this method is "an objective and quantitative method for evaluating estimate accuracy…" (Trost & Oberlender , 2003) The author feels that their claim of "the score of the estimate quantitatively measures the quality of an estimate" (Oberlender & Trost, 2001) is unjustified, since their study did not focus explicitly on quality, or presented any evidence of linking quality to accuracy. In summary, the limitations regarding their proposed method are: a) some of their elements are specific to construction industry type of projects, b) their methodology focused solely on the issue of accuracy (relating accuracy to the rating of these elements) and c) the elements "have been selected by the research team…", as Trost & Oberlender (2003) state.

2.4 Knowledge Elicitation

In this Section, the author introduces the concept of Knowledge elicitation (KEL) and a summary of the available KEL methods found within literature. These methods are reviewed for suitability against the various types of knowledge. Finally, a number of KEL methodologies found within literature are presented.

2.4.1 Introduction to Knowledge Elicitation

Casakin & Goldschmidt (1999) describe knowledge as "a structured representation that experts have acquired of a particular domain". KEL techniques aim to aid an elicitor in acquiring such knowledge, which in some cases remains tacit and is difficult for experts to externalise.

Eliciting knowledge is not a new concept and has been occurring in the past in many walks of life, taking many forms. The development of methods specific for eliciting knowledge has its roots in various disciplines such as "psychology, business management, education, counselling, cognitive science, linguistics, philosophy, knowledge engineering and anthropology" (Cooke, 1994). The emerging need since the 70s for computer-based systems, which are based on knowledge, highlighted the difficulties that exist in being able to elicit knowledge from humans. As a result, researchers placed an increased interest on knowledge elicitation techniques in order to cater for this complex part of the overall Knowledge Engineering process.

There are a number of different definitions that exist within literature regarding the process of knowledge elicitation. Greenwell (1988) describes knowledge elicitation as that area of knowledge acquisition which deals with acquiring information directly from domain experts. Cordingley (1989) states that knowledge elicitation is concerned with getting knowledge, predominately from human expert(s), and interpreting it. The working definition that she proposed is presented below:

> "(Knowledge Elicitation)…it consists of those activities undertaken by a person, the knowledge elicitor, in order to obtain material from any relevant source, analyse and interpret that material and put it in a pre-encoded form which, while useful to those who will encode the knowledge in the KBS language, also allows it to be scrutinised by all parties interested in Knowledge-Based System development" (Cordingley, 1989).

However, Cordinley's definition is largely influenced by the pre-assumed final use of the knowledge elicited; in that case, the development of a Knowledge Based System (KBS). Edwards (1991) defines a KBS as: "…a computer-based system which supports, or performs automatically, cognitive tasks in a narrow problem domain which are usually only carried out by human experts". Cooke (1994) provides a similar definition to Cordingley, quoting that:

> "Knowledge elicitation is the process of collecting, from a human source of knowledge, information that is thought to be relevant to that knowledge" (Cooke, 1994).

She adds that some methods are not predominately destined for eliciting knowledge from humans, but may also involve the elicitation of knowledge through non-verbal mediums such as documents. She proposes that knowledge elicitation is part of a broader process, the knowledge acquisition, thus, being in agreement with the above authors. Cooke's (1994) definition is the one that was adopted for the purposes of this study.

Knowledge elicitation is often described as the 'bottleneck' of the knowledge acquisition process (Olson & Reuter, 1987; Hoffman *et al*., 1995). Some of the challenges in the elicitation of knowledge include both availability, and identification, of the right experts, as well as the elicitation of useful knowledge from within the 'clutter'. Knowledge elicitation is often described as a form of expertise in itself (Schreiber *et al*., 2000), where the knowledge elicitor should possess some familiarity, and/or skill, with the method used.

2.4.2 Knowledge Elicitation Methods

There is a variety of KEL methods presented in literature that could be used for eliciting knowledge from experts. Various authors have provided classifications of the knowledge elicitation methods, either based on the type of knowledge that is elicited, or based on the way that this knowledge is elicited from the experts (Olson & Reuter, 1987; Cordingley, 1989; Meyer & Booker, 1990; Meyer & Booker, 1991; Winstanley, 1991; Wielinga *et al*., 1992; Cooke, 1994).

Olson & Reuter (1987) classify KEL methods into direct and indirect methods. Direct methods include the KEL methods that require direct reporting of verbalisable knowledge by the expert, and indirect methods are characterised as those methods that are less dependent on the verbal interaction between the expert and the elicitor. Direct methods include interviewing, questionnaires, observation and protocol analysis. On the other hand, indirect methods include techniques such as repertory grid analysis, hierarchical clustering, card sorting and laddering. A further extension of this classification divides knowledge elicitation techniques into direct, indirect, observational and machine based (Winstanley, 1991).

Cooke provides a detailed review of all the techniques that could be used for knowledge elicitation, including techniques that are not generally found within the knowledge engineering literature, originating in disciplines such as cognitive psychology, education, business management and anthropology (Cooke, 1994). She classified all the techniques into three main categories, based on the mechanics of the techniques themselves. The first family of techniques includes direct techniques, which are usually used when watching experts or talking with them, such as interviewing, observation, participation and task analysis. The second family of techniques are process tracing techniques, such as verbal reports, protocol analysis and decision analysis. And the third family includes conceptual techniques that are used to produce representations of domain concepts and their structure or interrelations, such as laddering, triadic elicitation, repertory grid, sorting and structural analysis.

A detailed account of the knowledge elicitation techniques, as well a description for each one, could be found in Cooke's paper (Cooke, 1994). In this Section, the author presents a summary of the most widely used techniques for knowledge elicitation.

Interviewing

Interviewing is one of the most frequently employed techniques, used for eliciting knowledge from experts (Olson & Reuter, 1987; Cordingley, 1989; Hoffman *et al.*, 1995). In most instances, a successful interview depends on the questioning skills of the elicitor and in general the way the interview is carried out. It requires the use of good communication skills, creating a common understanding between the elicitor and the interviewee, establishing trust and many other factors that could indirectly affect the outcome of an interview, due to dealing with different kind of individuals. It is that interaction with people where interviewing becomes a form of art in itself; as a result, the outcome of an interview relies heavily on how the elicitor will conduct it. There are various texts that focus particularly on interviewing skills and techniques (Scott *et al.*, 1991; Durkin, 1994). Interviews could be described as *structured*, *semi-structured* and *unstructured*.

Structured interviews are interviews in which the interviewer follows a pre-defined structure for the purposes of questioning the interviewee. Structured interviews are generally carried out following a questionnaire where the questions have the purpose of eliciting specific answers, rather than being of a generic nature. Domain specific probe questions, and/or generic probe questions, could also be used. The generation of the domain specific questions by the interviewer, necessitate some prior analysis of the knowledge domain (Hoffman *et al.*, 1995).

Semi-structured interviews are similar in nature with the structured interviews with the difference that although a set of predetermined questions exist, the questions do not have to be followed in the structured order like during a structured interview. For example, if the interviewer feels that a question that he planned asking early in the interview could be asked later on, or could be ignored completely, he/she could make those changes to the interview sequence 'on the fly'. In addition, questions tend to be 'open-ended', not forcing the interviewee to provide deterministic answers. Semi-structured interviews are the types of interviews that are used mostly, because they provide a structured enough way to carry out an interview, but at the same time provide the flexibility required in interviewing (especially in an industrial environment where the interviewer would have to deal with a wide variety of individuals).

Unstructured interviews are interviews that are carried out in a 'free-form' fashion, without having predetermined topic(s) or questions, or even a questioning sequence (Cooke, 1994). They usually take the form of an open dialogue between the elicitor and the interviewee (Hoffman *et al.*, 1995). They are best suited for the very early stages of the knowledge elicitation where the interviewer needs to get an initial broad view of a domain.

Observation

Observation is a powerful knowledge elicitation technique that could provide the elicitor with a rich view of how an expert solves a task (Cordingley, 1989; Cooke, 1994). Especially in the case of tasks where an expert would find it difficult to verbalise what s/he is doing, observation proves to be invaluable. However, in some cases, observing an expert carrying out a task, which the elicitor is not familiar at all with, could result in data that are difficult to interpret. Observation could be supplemented by written, audio or even video recording in order to capture every detail about the expert's actions. Although observational techniques have the advantage of minimal interference with subject's environment, one of the issues that should be noted is the bias that may be introduced in the data collected due to the presence of the elicitor, or due to the subject knowing that s/he is being observed.

There are three variants of the observation technique, the active participation, focused observation and structured observation (Cordingley, 1989; Cooke, 1994). Although observational techniques are passive on the part of the elicitor, in the active participation the elicitor is involved in the activities which are under observation. There are different views about the meaning and extent of the participation of the elicitor, such as Spradley's (1980) view where he considers the involvement of people in the studied environment, as participation. An observation task is referred as focused when the elicitor focuses on a very specific part of the observed environment. Structured observation is used when the elicitor already knows the specific features of environment that s/he wants to record, while the observation would be unstructured if the elicitor had no pre-conceptions about what is going to be important about the task in focus (Cordingley, 1989).

Variants could include the examination of an environment or object by the elicitor; not just observing individuals. Observing a process or a product could yield an initial understanding and 'feel' of how something works or operates within an environment.

Talk-through Case Study

Talk-through case study, or often referred as case study analysis, involves the use of real cases where an interview could focus on. The expert goes through a past case where the elicitor has the opportunity to focus the questioning on that case. This method is often referred to as talk-through case study analysis and is suitable to elicit casual, facts and procedural knowledge from experts. One of the main advantages of this method is that the use of a case, which experts are familiar with already, may 'trigger' the experts' memory to reveal to the elicitor facts that otherwise would be difficult to re-enact in their answers.

Two variants of the case study analysis are the forward scenario simulation and the critical incident method. Forward scenario simulation focuses on a single case where the elicitor provides the expert an initial description of a problem, and the expert is then required to solve the problem step by step (Cooke, 1994). Due to the cases being hypothetical, the elicitor must have a clear understanding of the domain in order to be able to 'generate' a sound case that will lead to the elicitation of useful knowledge. The critical incident method involves the selection of cases based on their importance (Cooke, 1994).

Content Analysis

Cooke (1994) defines content analysis, as a way of organising a mass of 'open-ended' material by objectively and systematically identifying specific characteristics. The material could be any document originating from the domain where knowledge is sought after, or an interview transcript (in which case is referred to, as Protocol Analysis). Documentation analysis is similar to content analysis, through often the analysis may not be systematic to such degree of detail; the reader does it intuitively. Gammack and Young (1985) identified that domain concepts could be best elicited through documentation analysis. A study found that documentation analysis was used 22% of the time (Cullen & Bryman, 1988). The challenge in content analysis is to define the categories that would be used as the concepts on which the analysis of phrases/words will be based on. Content analysis could also be used in the task of analysing interview transcripts.

Card-sorting

Card sorting is a way for an elicitor to understand how the expert conceptualises the knowledge domain (Cordingley, 1989). Elements of interest, which are already known by the elicitor, are written down on a set of cards. The expert is then asked to sort the cards into two piles based on their relatedness, and label the piles. Following that, to further divide these piles into more piles of close relatedness and label them, until the expert reaches to the point where s/he could not further sub-divide them. There are different variations of the card sorting technique, based on the way the cards are sorted (based on constraints, hierarchy and element attributes). Card sorting could be used in conjunction with an interview, as a focus for discussion and understanding of how an expert, or a group of experts, conceptualise a domain and the various concepts/objects within a domain.

Repertory Grid

The repertory grid technique is based on the Personal Construct Theory developed by Kelly (1955) and it is similar to the 'rating' techniques with the difference that a set of dimensions focus the ratings (Cooke, 1994). Following this technique, concepts or elements are identified and rated along dichotomous dimensions which are referred to as constructs (Cooke, 1994). The constructs could be provided to the expert, or be elicited by him/her, and the expert would rate them. A grid then could be constructed in which the constructs and elements would form the rows and the columns of the grid, respectively.

Rating (Scales)

Rating is an effective way for acquiring perceptions of experts regarding proximity estimations among various concepts. Different methods exist which rely on the rating technique. In the pair-wise comparison method an expert is presented with a pair of concepts and is asked to provide a rating of relatedness (Cooke, 1994). An alternative method is the magnitude estimation method in which the expert is presented with all the available pairs of concepts and is asked to rate each pair against another pre-selected pair, which has been selected as a reference point (Cooke, 1994).

More familiar methods typically applied within surveys and questionnaires, similar to the pair-wise comparison, include the Likert scales and the semantic differential scales. In both methods the expert is presented with a statement and a scale with categories associated with the points on the scale. The expert is asked to rate the statement based on the presented categories. As mentioned earlier, rating methods in general are very effective for eliciting perceptions. Perceptions as such are often subjective in nature and are difficult to quantify through the use of other methods (such as interviewing).

Laddering

The laddering technique is very useful in constructing hierarchies of a domain and the relations of its concepts (Schreiber *et al*., 2000). The result of this technique is a taxonomy of domain concepts (Cooke, 1994). Laddering in itself is a modelling technique where concepts are represented graphically, in a hierarchical way. The use of laddering during an interview can be very effective at both generating concepts and also structuring them. Rugg and McGeorge (1995) demonstrated the application of the laddering technique, in conjunction with a number of probe questions, for eliciting domain knowledge. Depending on the focus of the laddering exercise, ladders could be described as concept ladders, composition ladders, process ladders or attribute ladders. An additional advantage of using the laddering techniques as a way to elicit knowledge from experts is the resulting graphical representation, which allows the elicitor to understand the domain and the expert to quickly identify errors and inconsistencies.

The author presents a summary of the KEL methods reviewed, in Table 2.3, focusing on their advantages and disadvantages.

Table 2.3 – Advantages and Disadvantages of the KEL Techniques

Technique	Advantages	Disadvantages
Semi-Structured Interviews	– Ability to get a rich and in-depth insight into a domain – Discussion could deviate from pre-defined questions; thus given the possibility to elicit knowledge, not thought relevant before	– Time consuming (Hoffman *et al.*, 1995) – Large amount of qualitative data to analyse
Repertory Grid Analysis	– Uncover the structure of an unfamiliar domain (Schreiber at al., 2000)	– Constructs may not be equally applicable to all elements (Cooke, 1994) – Time consuming
Talk-through Case Study	– Effective at making Experts remember…why things happened – Experts often provide explanations and justifications to their actions	– Time consuming – Results depend on the case selected – The selection of 'good' cases lies with the judgement of the elicitor
Content Analysis	– Does not rely on having to interact with Experts – An elicitor develops a good initial understanding of a domain	– Identifying 'key' knowledge may be tricky and time consuming – Difficulty in determining appropriate categories (Cooke, 1994)
Card Sorting	– Suitable for structuring objects/concepts and determine relationships	– Requires that the elicitor has already identified some key concepts regarding the domain
Observation	– Can obtain a first-hand 'rich' understanding of a domain and its key concepts – Minimal interference with expert's task and environment (Cooke, 1994)	– Time consuming – Observation of humans may alter their behaviour and/or performance (Cordingley, 1989)
Rating	– Effective at quantifying perceptions – Suitable for eliciting tacit knowledge	– Requires a pre-identified set of concepts
Laddering	– Effective at generating useful taxonomies – A representation of the resulting hierarchy is 'concurrently' developed	– Inappropriate for domains that are not hierarchical in nature (Geiwitz *et al.*, 1990)

A summary of the main advantages and disadvantages of the KEL methods reviewed was presented. In the following Section, the author explores, through literature, the suitability of the KEL methods against particular types of knowledge.

2.4.3 KEL and Types of Knowledge

One of the main principles of knowledge engineering was the recognition that there are different types of knowledge (Shadbolt & Milton, 1999). Early notions differentiated knowledge to procedural and declarative, depending on whether the knowledge is related to 'know-how' or to mere 'facts'. Knowledge could also be described as explicit or tacit, depending on whether knowledge could be available to conscious introspection, or not. Thus, tacit knowledge is difficult to be articulated by experts. Differences as such, with regards to the types of knowledge, necessitate the use of different KEL techniques (Shadbolt *et al.*, 1995).

A list of the types of knowledge associated with engineering design is provided by the MOKA consortium (Stokes, 2001). MOKA development was initiated in 1997 with the primary objective of allowing the specific types of knowledge that are found within the engineering design domain, to be captured and represented following a structured methodology. The summary of the types of knowledge identified is listed below (these are the top-level categories):

- Terminology
- Product Specification
- General Constraints
- Conceptual Design
- Physical Design
- Design Rationale
- Design Purpose – activities
- Design Process – techniques
- Rules
- Strategy
- Associations

Taking a more holistic view, Rodgers *et al.* (2000) provide the following knowledge types found to exist in engineering design:

- **Explicit and Implicit** – Implicit knowledge is kept within the heads of the experts, usually difficult to express to other people (often referred to, as tacit); while explicit knowledge could be easily communicated to others

- **Heuristic** – Heuristic knowledge is often regarded as the expertise that is applied by an expert in solving a problem; often acquired through experience
- **Declarative and Procedural** – Procedural knowledge has to do with actions, decisions or processes that are carried out by the expert ('know-how'), while declarative knowledge consists of facts that somebody is aware of

As presented earlier, the realisation of the existence of different types of knowledge led to the development of particular KEL techniques to elicit such peculiar knowledge types. Table 2.4 presents Wellbank's (1987) findings, where KEL techniques are mapped against their suitability of eliciting specific types of knowledge.

Table 2.4 – Types of Knowledge against KEL Techniques (Wellbank, 1987)

	Facts	Conceptual Structure	Casual Knowledge	Rules	Weight of evidence	Procedures	Expert's strategy	System's strategy	Context of rules	Explanation	Justification
Interview	√	√	√	?	?		X		?		√
Talking through Case studies	√	X	√	√	X	√	X			√	
Observing interactions							√			√	
Protocol Analysis						√	√				
Card-sorting		√									
Multidimensional scaling		√									
Repertory grid		√	X	√	√	X	X				
Induction			X	√							
Task analysis								√			
User interviews								√			
Examining prototype				√	√				√	√	

√ = suitable, x = not suitable and ? = difficult, but possible

In the following Section, the author presents the KEL methodologies identified within literature.

2.4.4 Knowledge Elicitation Methodologies in Engineering Design

Although stand-alone KEL methods have been proved to be useful in eliciting knowledge from a particular domain, when used on their own they are not sufficiently effective at capturing a 'rich' view of that domain (Rush, 2002). They have their weaknesses and limitations in respect to which type of knowledge they can extract from expert(s), thus an elicitor should expect to use apply a combination of techniques, rather than relying on just a single one (Wright & Ayton, 1987; Hoffman *et al.*, 1995; Rugg and McGeorge, 1999).

As a result, it was deemed necessary to develop KEL methodologies consisting of a blend of techniques and a structured sequence of processes for an elicitor to follow.

A KEL methodology provides a structured approach, by utilising a number of the most suitable elicitation techniques (for that particular elicitation exercise), in order to extract a particular type of knowledge from experts. In addition (to the criteria presented in table 2.4), a number of practical considerations need to be taken into account during the design of a knowledge elicitation strategy. Klein *et al*. (1989) propose five criteria which they found to be relevant to their study. These include: 1) time needed to apply the methods, 2) cost-effectiveness of data collection and analysis, 3) timeliness of the results, 4) level of training of the knowledge elicitor, and, 5) packaging of the knowledge elicitation results.

Hoffman *et al*. (1995) observed some consensus amongst authors as to the typical stages of a knowledge elicitation strategy. This typically includes an initial stage where the use of documentation analysis, unstructured interviews and/or observation will provide to the elicitor with an initial understanding of the domain. After this period of familiarisation and development of initial understanding, the next stage is concerned with extending, refining and validating the knowledge through the use of structured interviews and/or contrived techniques. In the remaining of this Section, the author presents a number of KEL methodologies identified within literature. The author has purposely focused on 'pure' KEL methodologies, compared to overall Knowledge Modelling Frameworks applied in the area of knowledge engineering; such as MOKA (Stokes, 2001) and Common-KADS (Schreiber *et al*., 2000). The review of such Modelling Frameworks highlighted that these frameworks do not focus on the elicitation side of the knowledge engineering process.

XPat is a knowledge elicitation methodology developed for capturing process knowledge (Adesola, 2002), which application was demonstrated in the steel-making industry. The elicitor uses a set of structured templates, referred to as the 'brown paper exercise', in order to elicit knowledge from experts during a workshop. The elicitation is process driven where the elicitor tries to identify the inputs, processes and outputs from the expert. The results are modelled using an enhanced version of IDEF0, which serves as a graphical representation of the knowledge elicited by the expert.

Bailey (2003) developed the KEN methodology, which stands for 'Knowledge=Expert-Novice'. The proposed methodology is based on the view that knowledge is the difference between an expert and a novice. The methodology requires that the elicitor participates in the working environment and performs the same tasks an expert performs using the same tools as the expert. When the novice attempts to solve a task, (similarly to ones solved by experts), and faces some difficulties then consults the expert for help. It is claimed that with that process the novice learns by 'trial and error' how to solve a task, thus capturing that knowledge (Bailey, 2003). A disadvantage of the KEN methodology is the subjective interpretation of the novice; where s/he may introduce personal bias to the final results (Bailey, 2003). Another issue has to do with whether the novice can comprehend successfully what s/he is presented by the expert in terms of solving a task. Thus, there could be concerns with the application of the methodology in very complex and knowledge-intensive domains.

It was identified that the methodologies presented are process-driven and their focal point is the elicitation of process knowledge. The domains under which their development was based were all process-intensive, such as the steel-making and the cutting tools design industry. As presented earlier, the cost estimating knowledge which is developed through years of experience is largely domain-driven. As presented in Section 2.2.4, novices need guidance in order to carry out a task; both in terms of the process, but more importantly in terms of what they need to know in order to carry out the process. As a result, an elicitation methodology for CE knowledge, used by novice cost estimators, should provide guidance in the area of knowledge requirements. The author feels that these methodologies lack this sort of guidance. Subsequently, none of the reviewed methodologies were developed for addressing the needs of cost estimating.

2.5 Cost Estimating Knowledge Capture

As identified earlier the development of a cost estimate comes hand to hand with collecting data, and obtaining the necessary knowledge and understanding for the product/project for which the estimate is developed for. This section reviews the current processes existing for capturing cost estimating knowledge, with respect to developing a cost estimate.

2.5.1 Challenges in Eliciting CE Knowledge

Beltramo (1988) emphasises the need for thoroughly documenting both the methodology and the assumptions incorporated into a cost model. In practice, many of the assumptions made and the knowledge utilised by the cost estimator are not documented; and as a result, articulated to others. As presented earlier, one of the reasons is the lack of formalised processes which could be used to facilitate this activity.

The working group of the European Aerospace Cost Engineers (EACE) highlighted the need for identifying and implementing mechanisms for knowledge capture and retention for the purposes of cost estimation (EACE, 2004). In addition, they identified the problems in the capture of CE knowledge. They are: 1) Time consuming, 2) Costly, 3) No immediate benefit, 4) Overhead, and, 5) Not an individual's objective. Nevertheless they concluded that the potential advantages will outweigh these drawbacks. Similarly, NASA (2004) emphasises the importance that cost estimators should place on using improved processes for capturing CE knowledge for future cost models.

As presented earlier, cost estimating is a knowledge intensive task and it is up to the estimators to interact with engineers and/or process planners to elicit the necessary knowledge that they may be lacking. However, acquiring and maintaining the knowledge from the process planners is an extremely expensive process (Layer, 2002). In addition, one of the most difficult parts in acquiring data relating to a cost model is the identification of the 'right' experts (Meisl, 1988).

In addition, experts often face difficulties in articulating and sharing their knowledge (Durkin, 1994; Schreiber *et al.*, 2000). Currently, the elicitation of CE knowledge heavily relies on the cost estimator's skills; such as, having good people interface skills in order to be able to gather sound information (Schehr, 1989).

2.5.2 Review of CE Tools in Terms of Knowledge Capture

Commercial CE software tools were presented in Section 2.1.3. In this Section, the author reviews these tools in terms of their potential to capture cost estimating knowledge. The tools presented provide some means of storing cost data, in some way or another, thus making their re-use viable in the future. However, none of the commercial tools presented have the explicit means to capture the knowledge utilised by cost estimators during the development of an estimate. As a result, a number of assumptions made during the development of a cost estimate, are not captured in any explicit form. Such tools could potentially guide novice cost estimators in respect to the data required (in producing the cost estimate); however, they do not provide any guidance as to how the novice could acquire such data. As a result, the CE software tools are focusing on the data requirements, ignoring the overall picture regarding the knowledge that a cost estimator should have in order to develop a good estimate effectively and to the best representation possible.

The author observed that the CE software tools are very useful to cost estimators (especially in the early stages of the product lifecycle). However, the use of such tools necessitates that the cost estimator has some experience and judgement regarding the CE process. Some level of both cost estimating and domain experience is still required in both the manipulation and analysis of data. Due to the generic nature of these tools, the estimator should poses the appropriate judgement regarding the tool's output; and the ability to add/subtract and/or calibrate any cost areas which may differ due to the individualities of the product that is being estimated.

Rush (2002), in his study, arrived to similar conclusions, that commercial cost estimating tools lack the capability of being able to capture cost estimating knowledge concurrently with developing an estimate. He adds that the only feature towards capturing some of the assumptions is the availability of a notepad where users can make notes and save them along with the estimate; although by no means it provides a structured knowledge capture approach.

2.5.3 Current Attempts Identified in Literature

Throughout literature there is a limited amount of resources indicating the use of formal knowledge capture techniques for the purposes of acquiring cost estimating knowledge. A number of references are presented below, where knowledge capture methods were utilised for the purposes of acquiring CE knowledge.

Rueve (2001) developed a methodology for managing knowledge regarding the process of cross-checking cost estimates. The methodology is based on an existing knowledge management framework, and capitalises on existing knowledge elicitation techniques for the generation of knowledge regarding the cross-checking activities of cost estimates. The purpose and application of this methodology is quite specific to knowledge associated with estimates' cross-checking, and does not represent a full generic knowledge elicitation methodology which could be easily applied to alternative CE activities; thus, hindering its applicability on this study.

In situations where engineers could only provide their expert judgement rather than empirical data, the NASA (2004) propose the use of the Deplhi method for capturing and documenting the knowledge being shared from an engineer's expert opinion. The Delphi method (Brown, 1968; Dalkey *et al*., 1969) is essentially a focus group (consisting of the experts) where they try to converge on certain values/concepts through an iterative process of discussion and feedback. However the interviewing skills of the cost estimator are very crucial to the success of that task (NASA, 2004).

Rush (2002) applied the KEN methodology (presented in Section 2.4.4), in order to acquire knowledge relating to the calibration of the inputs of a software cost model. The context under which this methodology was applied is quite different to the context of this study. As presented earlier, the KEN methodology lacks in providing the necessary guidance to novices, both in terms of what knowledge is required, and in some cases how to elicit it. Based on observations from the review of literature, the author is suggested to believe that novices need direction in terms of the knowledge required to elicit, structured templates to capture such knowledge, as well as cues as to how to elicit the knowledge from experts. The KEN methodology exhibits some limitations in all these areas.

The review of the current methodologies regarding CE knowledge capture was presented. Initial observations point towards the lack of a formal knowledge elicitation methodology specifically developed to be used by cost estimators. The peripheral attempts identified, have a number of limitations: a) they are either too specific to a particular cost estimating activity (not tailored to eliciting knowledge regarding the development of a cost estimate for hardware mechanical products), b) they largely focus on the representation side of the captured knowledge, placing less importance on the actual elicitation of that knowledge in the first place, and, c) they do not provide to novice cost estimators guidance with regards to the CE knowledge that they should be acquiring in order to develop their estimate.

2.6 Summary and Key Observations

In Section 2.1, the author provided an overview of cost estimating, along with the available CE techniques and software tools. It was identified that parts of the cost estimating process are currently highly subjective, where estimators utilise their judgement and personal experience in developing a cost estimate. Finally, the typical purposes and uses of cost estimates were presented.

In Section 2.2, the author presented some of the challenges currently surrounding the CE process; particularly with regards to the knowledge requirements and their association to the product lifecycle. It was identified that:

- Cost estimating is a knowledge intensive process.
- Although it is widely recognised that an estimator's knowledge is key towards the development of a cost estimate, there is a lack of an in-depth study into the exact knowledge requirements (covering a holistic view; not just focusing on the data and information requirements).

In Section 2.2.3, literature accounts were presented regarding the skills of a cost estimator. Finally, in Section 2.2.4, the implications of expertise were presented differentiating experts from novices. It was identified that cost estimating expertise in particular is an on-going learning process. The author observed that:

- There is some confusion in literature regarding knowledge in cost estimating, where the term is often used inter-changeably to describe both knowledge regarding the domain and knowledge of the CE practices themselves (the latter, better described as the skills of a cost estimator).
- Inaccuracies to cost estimates are often the result of the lack of practical knowledge; novice cost estimators are particularly influenced by this phenomenon, since they lack all the practical knowledge regarding a domain and competence with respect to the skills required.
- Novices tend of follow rules and guidelines, since they lack the experience and intuitive grasp of situations that an expert possesses.

In Section 2.3, the author presented literature accounts regarding the current beliefs on the subject of good cost estimating. This review led to the identification of the CE best practices and their pitfalls. The author noticed that often good estimating is associated with accuracy. The author feels that accuracy in itself should not be a measure of how good a cost estimate is, since it could be misleading. As a result, it was identified that:

- There is a lack of an in-depth study in regards to what a good estimate is, in terms of quality.

In Section 2.3.4, the author presented the current practices found within literature with regards to the CE review process. The key observations are:

- Currently the review of cost estimates is a highly subjective process; usually carried out with the use of a checklist.
- The end result of the review is often not quantified in an explicit way, which could be easily compared to other estimate review results.

In Section 2.4, the author introduced the area of knowledge elicitation, listing the available KEL techniques found within literature. It was identified that individual KEL techniques are most suitable for eliciting some specific types of knowledge. Finally, the author presented some of the overall knowledge capture frameworks applied in different disciplines. It was identified that these methodologies largely focus on eliciting process-based knowledge. The key observations are:

- Current methodologies mainly focus on the modelling side of the knowledge acquisition process; placing less importance on the actual elicitation of that knowledge.
- Some of these methodologies lack the structured guidance that novices require.

In Section 2.5, the author presented some of the challenges in eliciting CE knowledge. It was identified that currently the elicitation of cost estimating knowledge relies on the skills and expertise of the cost estimators. Current methods were reviewed, and it was identified that they have some limitations regarding their use. Thus, the author feels that a complete knowledge elicitation methodology for the cost estimation of complex hardware mechanical products is lacking. The key observations are:

- There is a lack of available structured methodologies for eliciting cost estimating knowledge; this process currently relies on the estimator's skills and expertise, rather than on some formalised method.

- The review of some of the leading cost estimating software models revealed that they have weaknesses in terms of knowledge capture. There is not a formal process for capturing the rationale or the decisions made by the estimator that utilised the cost models.

The key observations of the literature review were summarised in this Section, highlighting potential areas for future research. It was identified that cost estimating is a knowledge intensive process, and novice cost estimators often lack the knowledge required in developing a cost estimate, since this knowledge is often acquired through the accumulation of experience in a domain. There is a lack of formal methodologies that cost estimators could utilise in order to acquire the knowledge for developing a cost estimate. In addition, it was identified that the process of reviewing cost estimates is currently highly subjective. The author will be addressing these key issues in the following Chapters, aiming to provide cost estimators with a structured KEL methodology, as well as a method for reviewing estimates which is less prone to subjective interpretations. In the following Chapter, the research objectives are defined based on the research gaps identified following the literature review.

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CHAPTER 3 – RESEARCH DESIGN

In the previous Chapter the review of the literature was presented, leading to the identification of the research gaps. One of the key observations of this review was the distinct lack of information regarding the knowledge needs of the CE process and the lack of formalisation surrounding the discipline area. In addition, it was identified that both the process for eliciting such knowledge and reviewing cost estimates are highly subjective, lacking of any formalism.

The purpose of this Chapter is to provide the reader with a complete account of how the research gaps identified in Chapter 2 led to the aim and objectives of this study, as well as the rationale towards selecting a suitable research strategy. In Section 3.1, the research aim is presented, and the corresponding objectives generated. Section 3.2 presents a review of the current research techniques along with the available research strategies, data collection techniques. In addition, it presents the steps that the author took in order to ensure the validity of the research study. In section 3.3, the author justifies the methodology, which was followed throughout this research in order to fulfil the research and summarises the overall research design. Finally, in Section 3.4 a summary and the key observations of this chapter are presented.

3.1 Research Aim & Objectives

The aim of this research study is:

> To develop a framework that will improve the perceived quality of cost estimates, by minimising the subjectivity involved in the CE process

The literature review in Chapter 2 served as a basis for identifying the current research trends and problematic areas within the overall domain. The key research gaps can be summarised as:

- Although cost estimating is a knowledge intensive process, there is a lack of focus on the knowledge requirements for cost estimating, especially in the case of complex mechanical hardware products; where knowledge and skills are often used inter-changeably in literature.
- There is a lack of available structured methodologies for eliciting cost estimating knowledge.

- There is a lack of an in-depth study into the factors contributing towards the quality of cost estimates. In addition, the cost estimate review process appears to be a highly subjective process, relying on the subjective perception of the reviewer.

As a result a number of objectives were defined with the purpose of fulfilling the aim of this study. The research objectives are:

- To identify through the review of the literature the key issues regarding the current CE practices; and explore their shortcomings.
- To improve the understanding about the knowledge utilised by cost estimators in developing cost estimates for complex mechanical hardware products; and propose a systematic approach for reducing the subjectivity in the way this knowledge is currently captured.
- To understand the perception of quality in cost estimates, within the industry.
- To minimise the subjectivity involved in the review process of cost estimates, by developing a structured method for assessing and quantifying their quality.
- To increase the formalisation of the current CE process, by providing novice cost estimators with a framework that they could utilise for improving the quality of their cost estimates.

In the following Section, the author reviews the available research strategies, leading to the formation of the research methodology of this study.

3.2 Research Methodology Formation

This chapter presents the methodology that is adopted in order to carry out the proposed research. Initially the context of the research is defined, a research strategy is selected and finally, issues concerning the data collection techniques used, are discussed.

3.2.1 Research Context

It is important to put into perspective the context where the research takes place, in order to 'tailor' the research methodology accordingly. This research focuses on the cost estimating part of Cost Engineering. In addition, the research focuses on the detailed bottom-up cost estimation of complex long-lifecycle hardware products. Due to the particular focal point on the generative-based CE techniques, the focus of this study is associated with the late conceptual, definition and development phases of a typical product design lifecycle. This study's context was defined based on the available industrial support to the researcher (sponsoring organisations), as well as on the gaps identified within the overall research area.

3.2.2 Qualitative and Quantitative Inquiry

There are two distinctive approaches to research design: 'quantitative' or 'qualitative' (Gummesson, 1991); also described as 'fixed' or 'flexible' designs, in some texts (Robson, 2002).

A quantitative approach is chosen when the phenomena of interest are typically quantified (Robson, 2002). That means that the majority of the data collected, and used to base the analysis upon, is of numerical format. A distinct characteristic of quantitative research is the use of a controlled environment, where the researcher has full control on both the environment and the experimental conditions (often referred to as 'variable(s)'). In quantitative research the researcher is 'detached', in order to eliminate the effect of influencing the research findings (Robson, 2002).

Creswell (1998) describes qualitative research as: "an inquiry process of understanding based on distinct methodological traditions of inquiry that explore a social or human problem. The researcher builds a complex, holistic picture, analyses words, reports detailed views of informants, and conducts the study in a natural setting". The exploratory nature of qualitative research results into the evolution of the research questions and ideas, as the research progresses and the researcher learns more about the research problem and the environment.

A distinct difference between qualitative and quantitative research is that quantitative researchers work with a few variables and many cases, while qualitative researchers rely on many variables and a few cases (Creswell, 1998). Thus, it is difficult to implement a quantitative design in the study of a social or natural setting, as there are many variables that cannot be controlled by a researcher. In addition, in qualitative research the researcher tends to be involved with the study.

A qualitative approach was adopted for this study due to a number of factors. The overall topic needs to be further explored, in order to generate ideas and fulfil the research objectives. In addition, there is a need to present a detailed view of the topic by studying individuals, in their natural setting. This would be difficult to do following a quantitative approach, as human subjects are very complex to study and establishing a controlled environment would be hard to achieve.

3.2.3 Research Purpose

In the previous Section, the research objectives were presented and the research focus was defined. The next step into designing the research methodology is the selection of a research strategy. However, in advance of selecting a suitable strategy it is important to understand the purpose of the research. The purpose of a research could be *Exploratory*, *Descriptive* and/or *Explanatory* (Robson, 2002). In Figure 3.1, a graphical representation of the correlation between the research questions, the purpose of the study and the research strategy, is presented. The purpose of the research will help determining which research strategy fits most to the nature of the research.

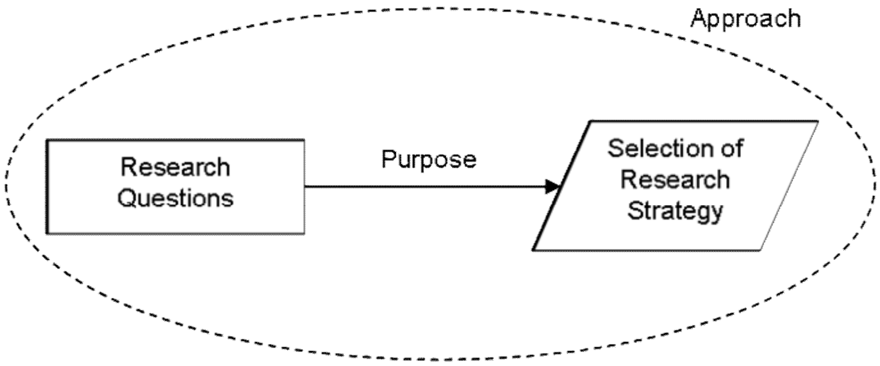


Figure 3.1 - Design of the Research

The research objectives are directly linked to the research questions. Considering the objectives and the context of this research the overall purpose of this study could be best described as exploratory. It should also be noted that a qualitative research approach is typically linked to exploratory research (Creswell, 1998; Robson, 2002).

3.2.4 Selection of a Research Strategy

Once the purpose of the research was defined the next step was to decide upon a suitable research strategy in order to carry out the inquiry. Throughout literature there are various references to what the traditional research strategies are, regarding a qualitative research inquiry. Creswell (1998) has carried out an extensive review of all these different 'points of view', by looking at various disciplines within a qualitative research setting. He summarised his findings into five traditional research strategies, widely acceptable for qualitative inquiries (Creswell, 1998). Figure 3.2 presents his findings, as well as providing the relationships for when each strategy should be used. Similarly, Robson (2002) concludes on three qualitative design research strategies: *Case Study*, *Ethnographic study* and *Grounded Theory study*.

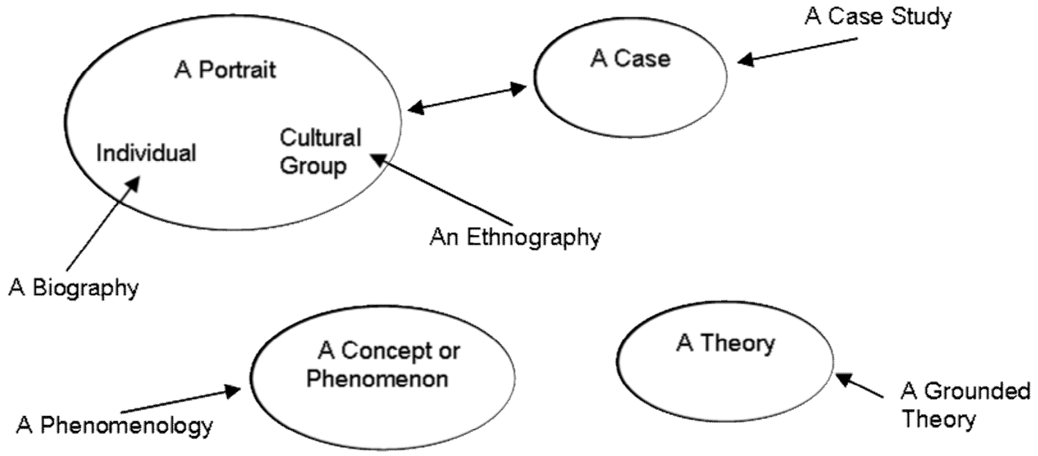


Figure 3.2 - Differentiating Traditions by Foci (Creswell, 1998; p. 37)

Before selecting a suitable research strategy a number of factors were taken into account. Factors as such include the context and focus of the research, as well as the available data collection methods to a researcher. Table 3.1 presents a comparison of the five strategies presented by Creswell (1998).

Table 3.1 - Comparison of Five Research Traditions in Qualitative Research (Creswell, 1998; p. 65)

	Biography	Phenome-nology	Grounded Theory	Ethnography	Case Study
Focus	Exploring the life of an individual	Understand the essence of experiences about a phenomenon	Developing a theory grounded in data from the field	Describing and interpreting a cultural and social group	Developing an in-depth analysis of a single or multiple cases
Discipline origin	Anthropology Literature, History, Sociology, Psychology	Philosophy, Sociology, Psychology	Sociology	Cultural anthropology, Sociology	Political Sciences, Sociology, Urban studies, other Social sciences
Data collection	Primarily interviews and Documents	Long interviews with up to 10 people	Interviews with 20-30 individuals to "saturate" categories and detail a theory	Primarily observations and interviews with additional artefacts during extended time in the field	Multiple sources – documents, archival records, interviews, observations, physical artefacts
Data analysis	Stories, Epiphanies, Historical content	Statements, Meanings, Meaning themes	Open Coding, Axial Coding, Selective Coding, Conditional Matrix	Description, Analysis, Interpretation	Description, Themes, Assertions
Narrative form	Detailed picture of an individual's life	Description of the "essence" of the experience	Theory or theoretical model	Description of the cultural group behaviour	In-depth study of a "case" or "cases"

Based on the comparison of the available research traditions, the use of case study as a research strategy was found to be most suitable. The selection was based on various considerations regarding the industrial sponsors' involvement, the research setting and the research focus. In addition, due to the context of the overall study there is a need to validate the results in an actual industrial environment, with great depth of detail. Another reason for selecting case study strategy, instead of any of the other available traditions, is the overall purpose of the research. Robson (2002) associates the use of case studies to exploratory work. This view is also supported by Gummesson (1991).

Case Studies Issues

As presented earlier, following a case study strategy is associated with developing an in-depth analysis about a 'single' case, or a small number of related cases, typically involving multiple methods of data collection (Creswell, 1998; Robson, 2002; Yin, 2003). Case studies are in use as an established method of research strategy for many years, applied in various research disciplines. Similar to all types of qualitative research studies, an issue with using a case study strategy involves obtaining access to the environment under study and establishing rapport (Creswell, 1998). However, due to the extensive involvement of the researcher and the human nature of the subjects, there is a potential risk of introducing bias to the study.

In an effort to minimise bias and any other potential risks to the validity of the study, the researcher has to prove that his research is trustworthy. To establish trustworthiness, the potential risks have to be identified and as a result, pro-active actions need to be undertaken. The following Section presents the necessary actions towards establishing trustworthiness.

3.2.4 Establishing Trustworthiness

In order to establish the research trustworthiness of a study there are two key areas that need to be addressed: the *validity* and *generalisability* of that research. Figure 3.3 presents a simple hierarchical order of the issues that need to be addressed in order to establish research trustworthiness, in a qualitative research inquiry.

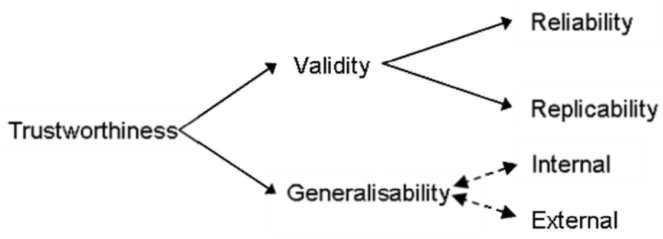


Figure 3.3 - Research Considerations in Establishing Trustworthiness

Validity

Validity is concerned with identifying whether a piece of qualitative research is accurate, correct, or true (Robson, 2002). There are several threats to validity that if addressed in advance by the researcher, could be minimised and/or eliminated. Robson (2002) lists three common categories of threats to qualitative research validity:

- **Reactivity** - "refers to the way in which the researcher's presence may interfere in some way with the setting, which forms the focus of the study, and in particular, with the behaviour of the people involved" (Robson, 2002, p. 172).
- **Respondent bias** - "can take various forms ranging from obstructiveness and withholding information – when, for example, the researcher is seen as a threat - to when the respondent tries to give the answers or impressions which they judge that the researcher wants" (Robson, 2002, p. 172).
- **Researcher bias** – "refers to what the researcher brings to the situation in terms of assumptions and preconceptions, which may in some way affect the way in which they behave in the research setting, perhaps in terms of the persons selected for observation or interview and the types of questions asked" (Robson, 2002, p. 172).

There are a number of strategies that could be adopted for dealing with these threats. These are (Creswell, 1998; Robson, 2002):

- **Prolonged involvement** – the researcher spends some time within the research setting, where s/he develops relationships with the participants and understands the culture of the setting studied. However, prolonged involvement could potentially increase the researcher bias.
- **Triangulation** - the use of different methods, sources, investigators and theories, to enhance the rigour of the research.
- **Peer debriefing and support** – it can help reduce researcher bias though debriefing sessions following long periods within the research setting.

- **Member checking** – it involves the follow-up with respondents where the collected material (transcripts, accounts and/or interpretations made by the researcher) is presented back to them (typically for review and validation). 'Member checking' is considered as crucial towards establishing credibility of the research (Creswell, 1998).
- **Negative case analysis** – applying the working hypothesis/theory in light of negative or disconfirming evidence. This quite often leads to a more elaborated/refined version of the theory (Creswell, 1998; Robson, 2002).
- **Audit trail** – keeping a full record of all activities while carrying out the research. It could be done in the form of transcripts, field notes, journal and/or details of coding and data analysis.

Table 3.2 provides a summary of how the threats to research validity can be controlled by applying the proposed strategies. In section 3.3, the author discusses how these strategies could be used to minimise the potential threats to the validity of the research study presented in this thesis.

Table 3.2 - Strategies for Dealing with Threats to Validity (Robson, 2002; p. 174)

	Threats to Validity		
Strategy	**Reactivity**	**Researcher bias**	**Respondent bias**
Prolonged involvement	Reduces threat	Increases threat	Reduces threat
Triangulation	Reduces threat	Reduces threat	Reduces threat
Peer debriefing and support	No effect	Reduces threat	No effect
Member checking	Reduces threat	Reduces threat	Reduces threat
Negative case analysis	No effect	Reduces threat	No effect
Audit trail	No effect	Reduces threat	No effect

In the remaining part of this Section, the author presents the issues concerning the reliability and generalisability of a research inquiry.

Reliability

Reliability in qualitative research is related to whether the methods and practices used are reliable. This would involve the use of structured and consistent data collection methods, as well as the use of a structured research strategy. Reliability is closely related to replicability, which is concerned with whether another person(s) studying the same phenomenon comes to the same findings. In order for a research study to be valid, it has to be ensured that it is reliable in the first place. However, if the research is reliable it does not necessarily mean that it is valid too. To achieve reliability the researcher would have to be honest and thorough into carrying out the research and in general providing an audit trail (Robson, 2002).

Generalisability

While validity is concerned with whether the results of a research are 'real' and 'true', generalisability is related to whether the results of a research study are generally applicable; it could be in other contexts, situations or times, or to persons other than those directly involved (Maxwell, 2002; Robson, 2002). In qualitative research there are two forms of generalisability: internal and external. The former refers to the generalisation of findings within the community, groups, or institution studied to person, events and settings that were not directly involved in the initial study (Maxwell, 2002). In contrast, the latter involves the generalisation of the conclusions to other research settings, groups or institutions. It is believed that external generalisability is difficult to achieve in a qualitative inquiry, for the reason that the theory/findings makes only sense to that particular individual(s) or setting(s) studied.

3.2.5 Data Collection methods

In a case study research it is essential to utilise multiple sources of data collection, where a chain of evidence is presented along with a record of the data (Creswell, 1998). The use of different sources of data, as well as different methods of data collection to elicit the same data, provides triangulation. It also ensures that both the data and the people/documents are reliable and credible. Although a qualitative study is mainly dealing with qualitative data, the collection of quantitative data could also be included in the approach (Robson, 2002).

The literature review contributes to the development of the initial ideas regarding the current methods, techniques and knowledge, and is essential towards developing a concise understanding of the domain. A number of data collection methods were employed during the data collection stage of this research study. They include interviewing, document analysis, observation, talk-through case study analysis and 'member checking'. In addition, a survey was carried out across a number of experienced cost practitioners in order to gain an understanding of the perceived quality of cost estimates.

3.3 Research Methodology Design

The author demonstrated his rationale regarding the decisions undertaken in shaping the design of this inquiry and evaluating the current research approaches, widely accepted in literature. The proposed research methodology is presented in Figure 3.4. The research methodology consists of three main stages: 1) research approach, 2) data collection and ideas formation, and, 3) data analysis and validation.

The purpose of the first stage, 'research approach', was to review the available approaches and to decide on a suitable research strategy. The purpose of the research was defined as being exploratory due to the nature of the research objectives. Both quantitative and qualitative approaches were considered, where a qualitative approach was selected. Finally, the available research traditions for qualitative type of inquiries were presented, and the 'case study' was selected as the most suitable strategy to carry out this study.

The purpose of the second stage of the research, 'data collection and ideas generation', was to select suitable data collection techniques for interacting with the research setting, in order to identify research issues and problematic areas. That would form the basis for developing new ideas on how to improve these areas. As presented earlier, the author needed to undertake a number of pro-active actions in order to minimise the threats to the validity of his work. Based on the review of the threats identified in Section 3.3.1, the researcher decided to adopt the following actions:

- Prolong his involvement in the research settings where the case studies will be based upon; subject to any practical constraints. This also ensures that the required access and rapport are established with key people in those settings. The prolonged involvement will minimise reactivity and respondent bias, as the researcher will not be seen as a threat or an outsider.
- Triangulation of data collected, sources of data and techniques used for data collection. Multiple techniques were employed, such as interviews, participant-observation, document analysis, survey and talk-through case studies. Triangulation also ensured that the researcher bias is minimised, even if there was a potential prolonged involvement within the research setting.
- Using 'member checking' to validate all the data collected, as well as to ensure that the researcher did not introduce any bias due to his own interpretation.

- Keep an audit trail of all the activities throughout the duration of the research study; thus, minimising researcher bias. Keep notes, audio records of interviews, whereas possible, and a research journal during all interactions with the research setting and key individuals.

The selection of suitable case studies was based both on the availability of support to the researcher at that time and the overall context of this study. The review of the literature in the area of cost estimation helped the researcher in identifying the problematic issues in the subject area. It contributed towards the development of new ideas. The literature review was an on-going process throughout this research, and coupled with the data collection from industry, enabled the researcher in maintaining both a theoretical and practical understanding of the research issues.

In Chapter 4, the author presents the modelling of the CE process across the collaborating organisations. The findings highlighted areas of weaknesses within the current CE process. These were particularly related to the way that cost estimators elicit knowledge for developing cost estimates, as well as the lack of formalised methods for assessing cost estimates and ensuring the achievement of quality in the CE process. In addition, the review of the literature brought to light new research gaps related to the overall aim of this study. A survey was carried out across the subject domain, in order to develop an understanding with regards to the factors contributing to the quality of a cost estimate (see Chapter 5). The results of the survey, together with the initial case study results and the data collection exercises led to forming the idea regarding the development of a framework that will enable novice cost estimators in producing cost estimates of quality similar to that of an expert (see Chapter 7).

The third, and final, stage of the methodology was the 'data analysis and validation' stage, where the development and validation of the proposed framework took place.
Initially, the results of the survey were utilised in developing a novel tool, which could be used to assess and quantify the quality of cost estimates. The effectiveness of the software tool was tested by independent experts from the subject area, across 9 test-cases; three of which corresponded to the case studies, where the tool was applied as an integral part of the overall framework (see Chapter 6). Based on the identification of knowledge and the characteristics of a good quality cost estimate, during the data collection stage, a framework was proposed. The framework

consisted of two distinct parts: a) a KEL methodology (the development of which is presented in Chapter 7), and, b) a tool for assessing and quantifying the quality of cost estimates (presented in Chapter 6). Two case studies were carried out, within two aerospace settings, where the framework was applied in order to test its applicability and effectiveness. Finally, a third case study was carried out within an automotive setting, in order to find out whether the research findings could be generalised to other industries. Finally, the research findings, limitations, conclusions and future recommendations are presented in Chapter 9.

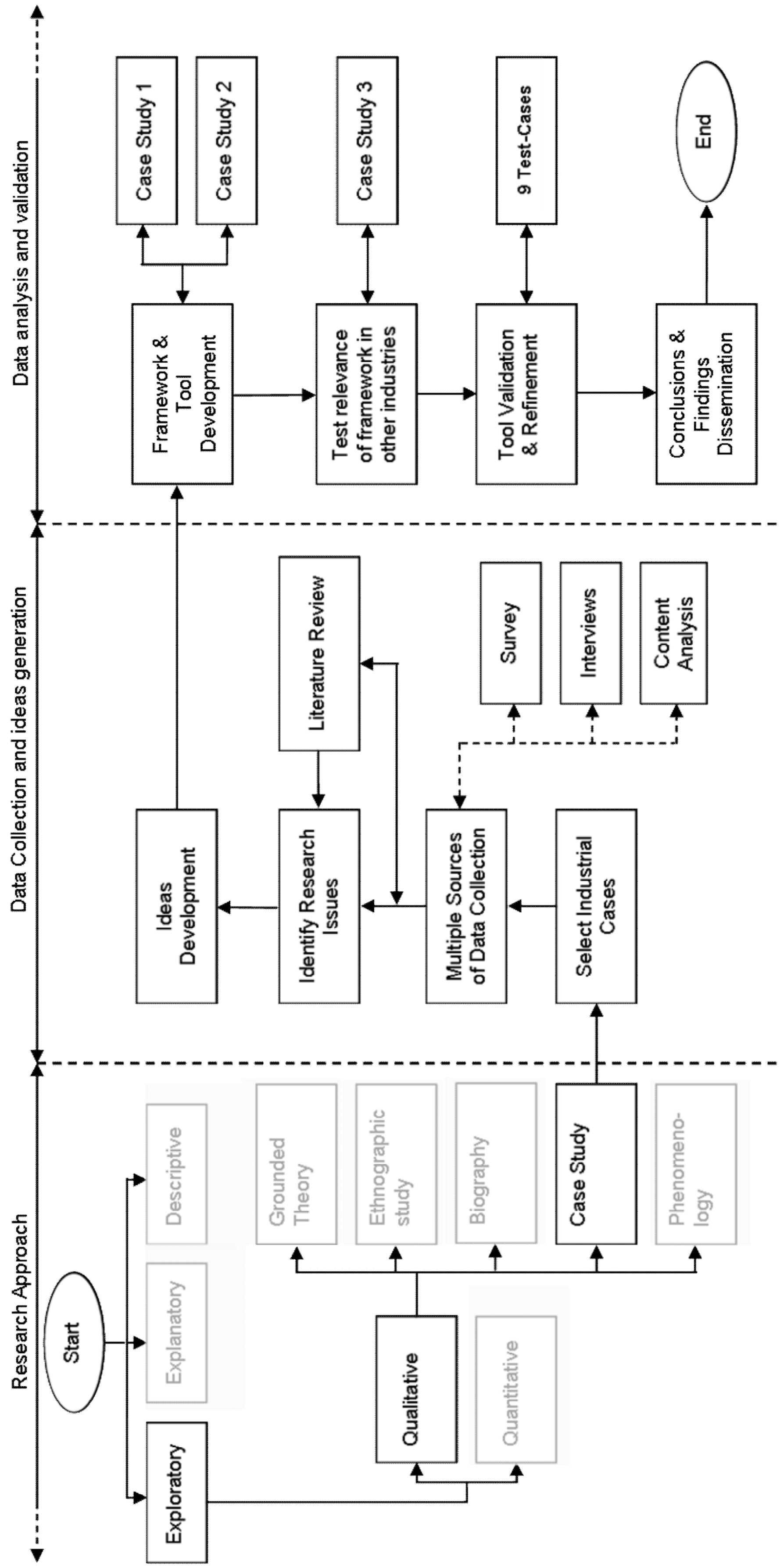


Figure 3.4 - Research Methodology Design

3.4 Summary

In Section 3.1, the research aim and objectives were presented. In Section 3.2, the available research strategies and approaches widely accepted within the research community were reviewed. A qualitative approach was selected due to the research's exploratory nature. In addition, a case study strategy was selected based on a comparative analysis of five qualitative research traditions. The issues of validity, generalisability and reliability, related to the selected approach, were discussed. Finally, in Section 3.3, the research methodology was presented, together with a detailed description of each stage of the research and the actions that the researcher took in order to minimise the threats to the validity of this study.

In the following Chapter, the author provides an overview to the knowledge surrounding the cost estimation of complex hardware mechanical products. The initial data collection results are presented from the research environment. The use of structured approaches, such as semi-structured interviews, IDEF0 modelling, analysis of documents and participant observation, led to the identification of the types of knowledge in the cost estimating process and to the initial identification of some of the development criteria for the proposed framework.

CHAPTER 4 – COST ESTIMATING KNOWLEDGE

In Chapter 3, the research objectives were defined for fulfilling the aim of this study. A suitable research strategy was selected in order to carry out this study and a research plan was proposed. In order to satisfy the overall aim of this study it was identified that the author first needs to establish an in-depth understanding of the cost estimating knowledge, as well as an understanding of the current practices and their shortcomings.

The aim of this Chapter is to investigate the knowledge requirements of the cost estimating process of complex mechanical hardware products. A formal representation of the CE activities was captured, through interviews and observation by the author within the collaborating organisations. The author followed a sequence of steps necessary to identify the types of CE knowledge, based on the CE process model. The first step included the analysis of the data and information requirements, utilised during each step of the CE process, and the second step involved the categorisation of these data nuggets into a hierarchical taxonomy (at knowledge level). The steps followed leading to the identification of the types of knowledge in CE, are presented in Figure 4.1.

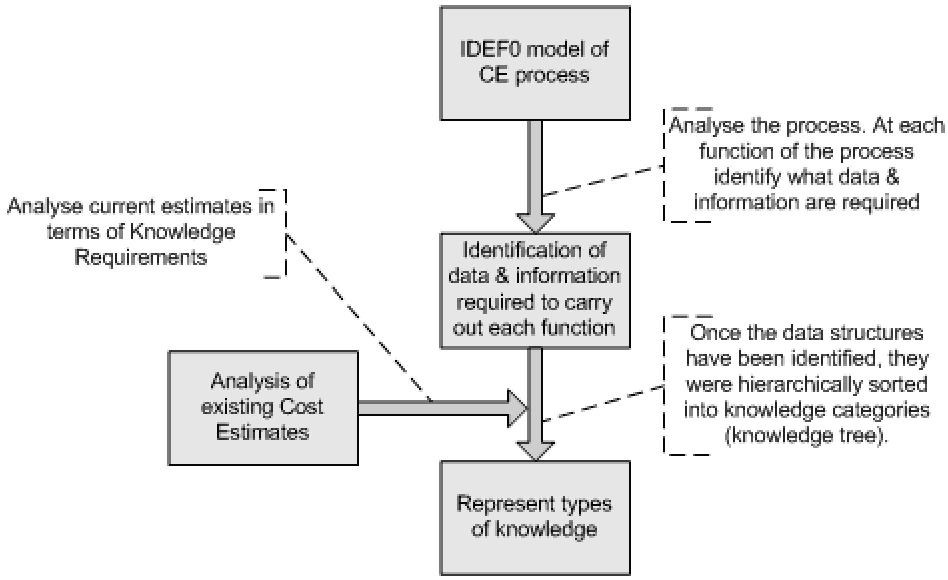


Figure 4.1 – Research Approach for Identifying the Types of CE Knowledge

In section 4.1, the cost estimating practices within the aerospace industry are reviewed, and captured using a formal modelling technique (IDEF0). In addition, a description is provided regarding the Request for Quote (RFQ) process which takes place between OEMs and suppliers; and how this impacts on their cost estimating needs. In Section 4.2, an introduction is given regarding the knowledge required in CE, along with the proposition of some crucial definitions to this study. The identification of the types of knowledge identified in CE is presented in Section 4.3. In Section 4.4, the types of knowledge identified are summarised and further described in terms of their characteristics.

4.1 Modelling the Cost Estimating Process

In order to identify the knowledge required in cost estimating, firstly it is important to review and thoroughly analyse the CE process. The IDEF0 modelling technique was used to develop formal models of the detailed bottom-up cost estimating process, based on interviews and the interaction of the author with the collaborating organisations. The interviews carried out and their results, contributing to the development of IDEF0 models, are presented in Section 4.3.1. In addition, the resulting model was based on the study of the CE processes within the collaborating organisations.

4.1.1 IDEF0 Modelling of the CE Process

The Integration Definition Function Modelling (IDEF0) modelling language was the outcome of the initiative of the United States Air Force program for Integrated Computer Aided Manufacturing (ICAM), back in the 1970s. IDEF0 is used to model the function of a system in a formal way (IDEF0, 1993). The technique provides a formal model in a descriptive form (graphical representation), with precise syntax and semantics. IDEF0 is described as an engineering technique for performing and managing needs analysis, defining requirements, functional analysis and design of systems.

The IDEF0 technique was selected for modelling the cost estimating process due to four reasons:

1. It is a well accepted and proven modelling technique
2. It provides a way to represent the activities of the cost estimating process; as well as the data and resources which flow into the various activities of that model
3. It provides a formal representation of a model, together with the syntax and its semantics

4. It results into a simple graphical representation, which can be easily understood and validated by third parties

Each function within an IDEF0 model is influenced by one or more Inputs, Controls, Outputs and Mechanisms (ICOMs). Figure 4.2 is a typical function found in an IDEF0 model, represented by a box shape.

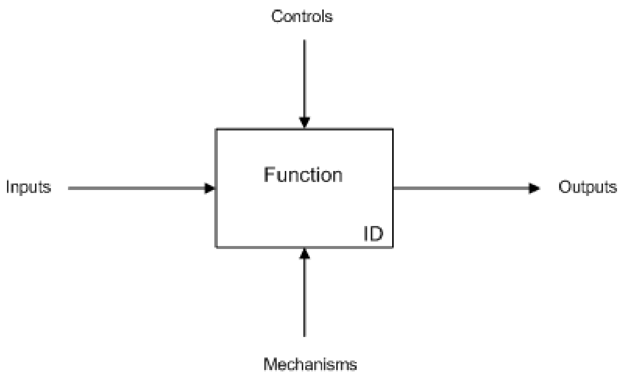


Figure 4.2 – Example of a Function Used in IDEF0 Modelling

The functions of the IDEF0 model were analysed in order to identify the necessary steps in the development of a cost estimate using the detailed bottom-up technique. Figure 4.3 demonstrates the IDEF0 model at node A0, showing the top-level inputs, outputs, Mechanisms and Controls to the estimation process.

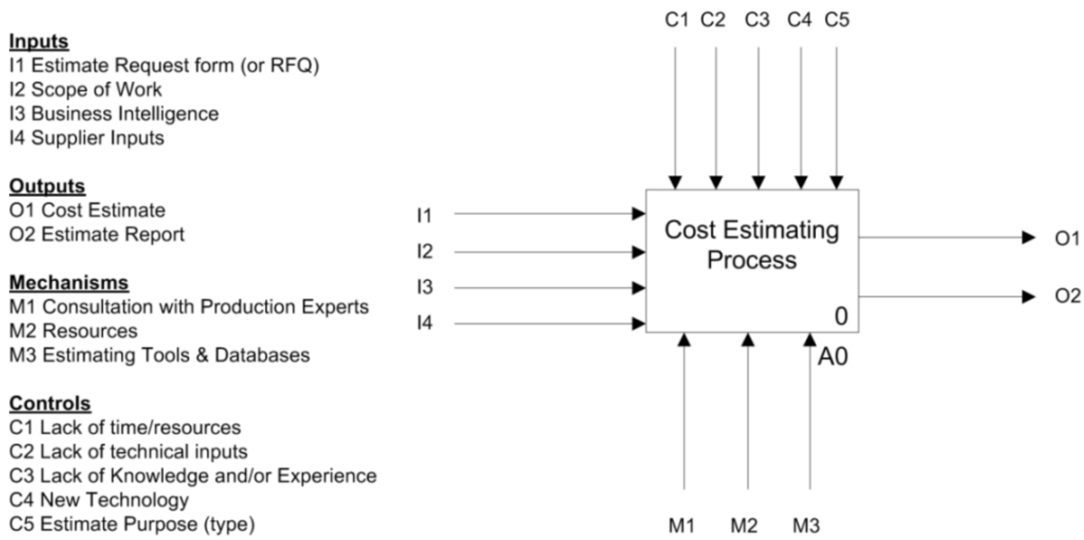


Figure 4.3 – 'Cost Estimating Process' Function

Figure 4.4 demonstrates the IDEF0 model at node A0, showing the steps involved in the cost estimating process.

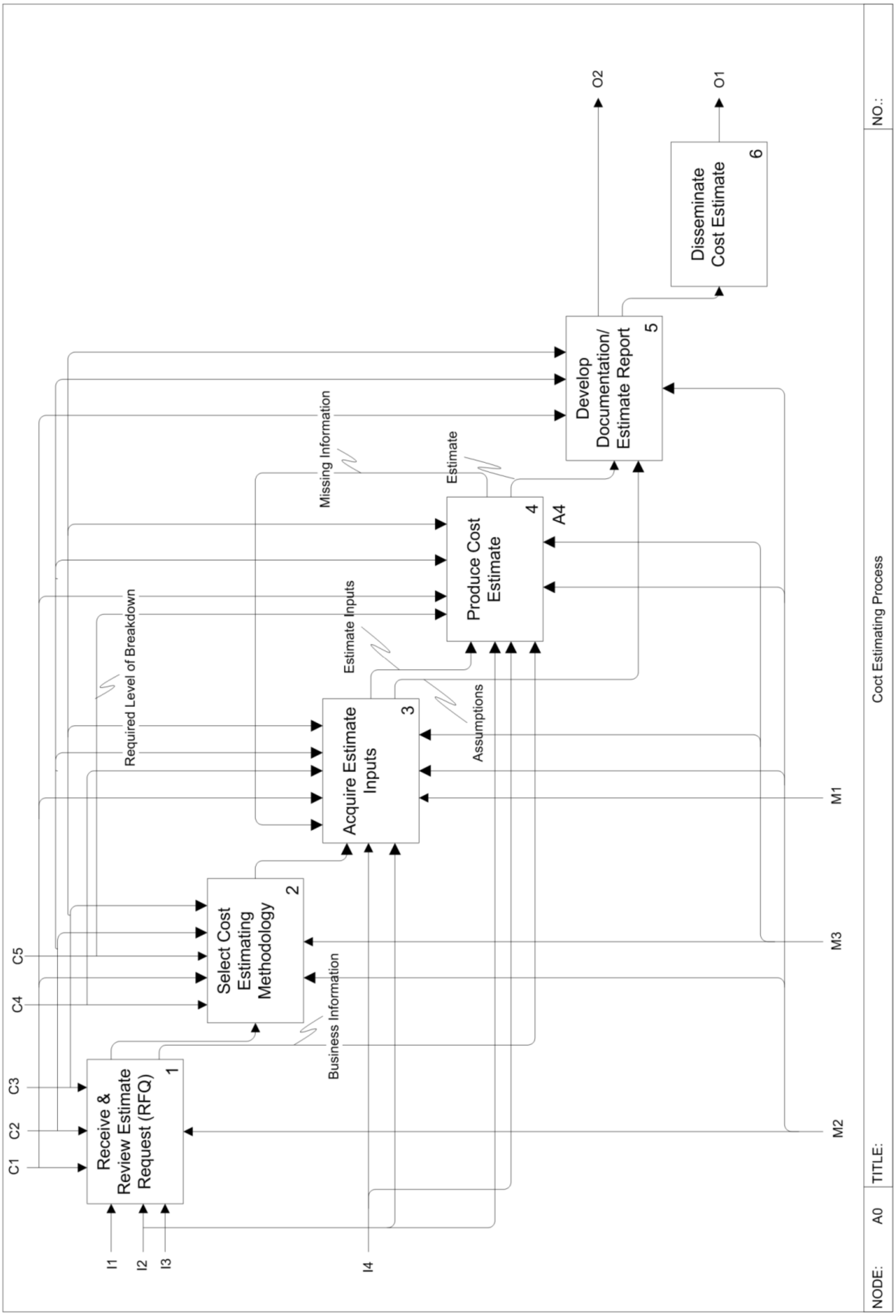


Figure 4.4 – Cost Estimating Process (Node A0)

Figure 4.5 demonstrates the IDEF0 model at node A4, showing the steps required for producing a cost estimate.

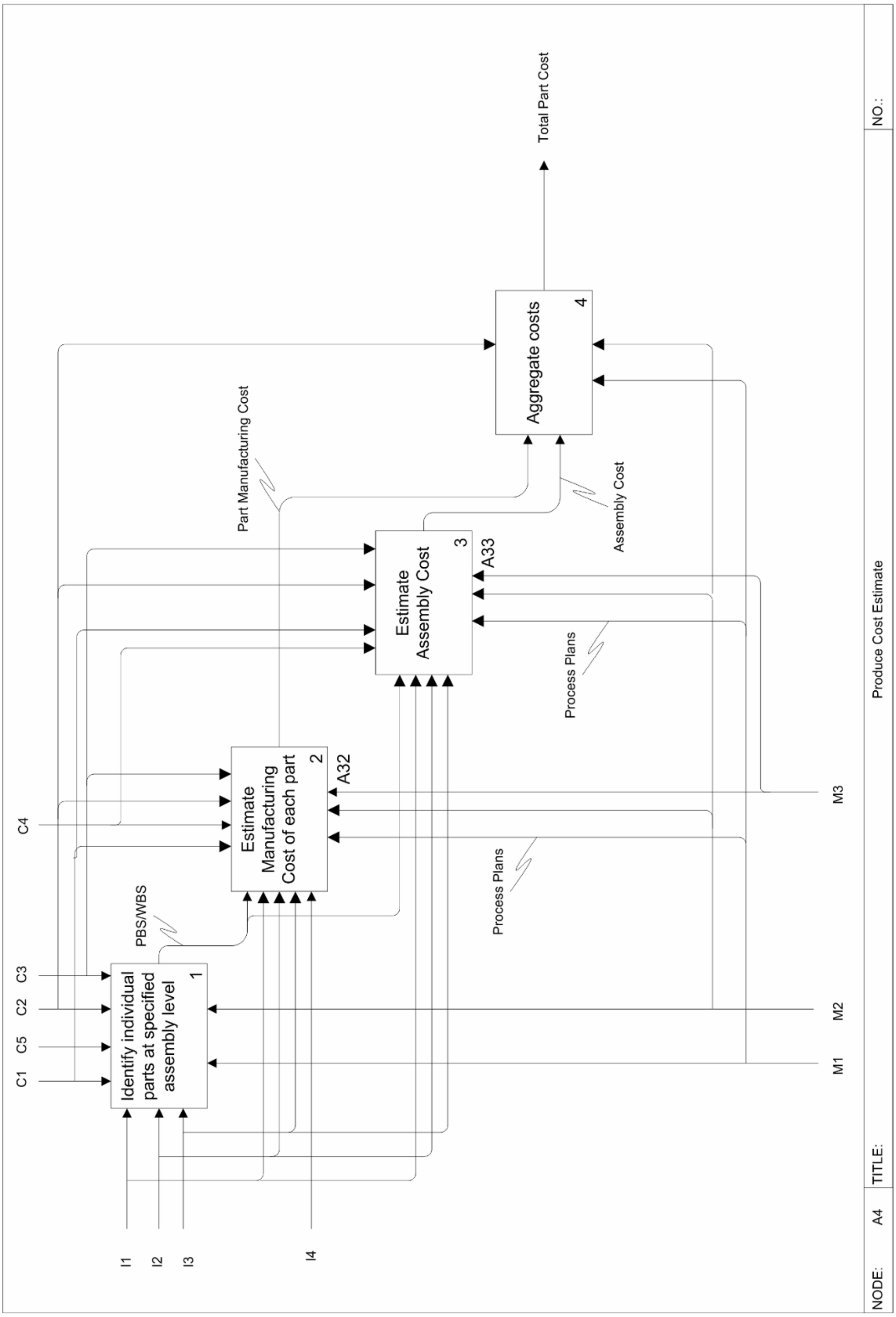


Figure 4.5 – Producing Cost Estimate (Node A4)

The full list of the IDEF0 models is presented in Appendix B, providing a further breakdown within some of the functions. The author provides a discussion of the current CE processes, based on the analysis of the IDEF0 models, in Section 4.3.2.

4.1.2 Detailed Bottom-up Cost Estimating

An introduction to the detailed bottom-up technique was presented in Chapter 2, Section 2.1.1. The interaction of the author with the collaborating organisations enabled him to understand in more depth the process of estimating the cost of a mechanical product, by utilising this technique. In this Section, the author attempts to focus on some additional issues surrounding the technique that emerged following the interaction of the author with experts from within the collaborating organisations.

A detailed cost estimate using the bottom-up approach is generally used in the later stages of development, once a product is more clearly defined. Figure 4.6 represents a typical product lifecycle in the aerospace industry (the example in the Figure is based on an OEM's perspective), and indicates when it is more likely to use this cost estimating technique. Of course, the detailed bottom-up technique could also be used during earlier stages; however, the estimator may face problems regarding the available information and well-defined inputs that are present to him/her during that lifecycle phase. The estimator would have to make numerous assumptions to compensate for the lack of certainty regarding the product definition.

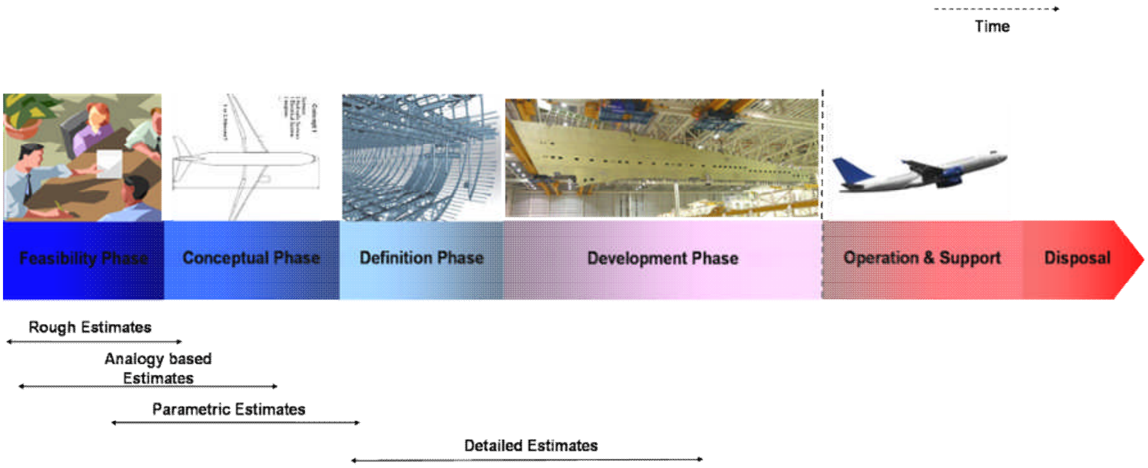


Figure 4.6 – The Use of Cost Estimating Techniques across the Product Lifecycle (Lavdas et al., 2005)

The process although it may slightly vary from organisation to organisation, in all cases it essentially follows a common basic structure (presented in Figure 4.7). For each process/activity associated with the *making* of a part, all labour and material resources are estimated in detail; along with any overheads incurred. Once the total cost has been aggregated, the general and administrative (G&A) costs are added to form the total part/product cost.

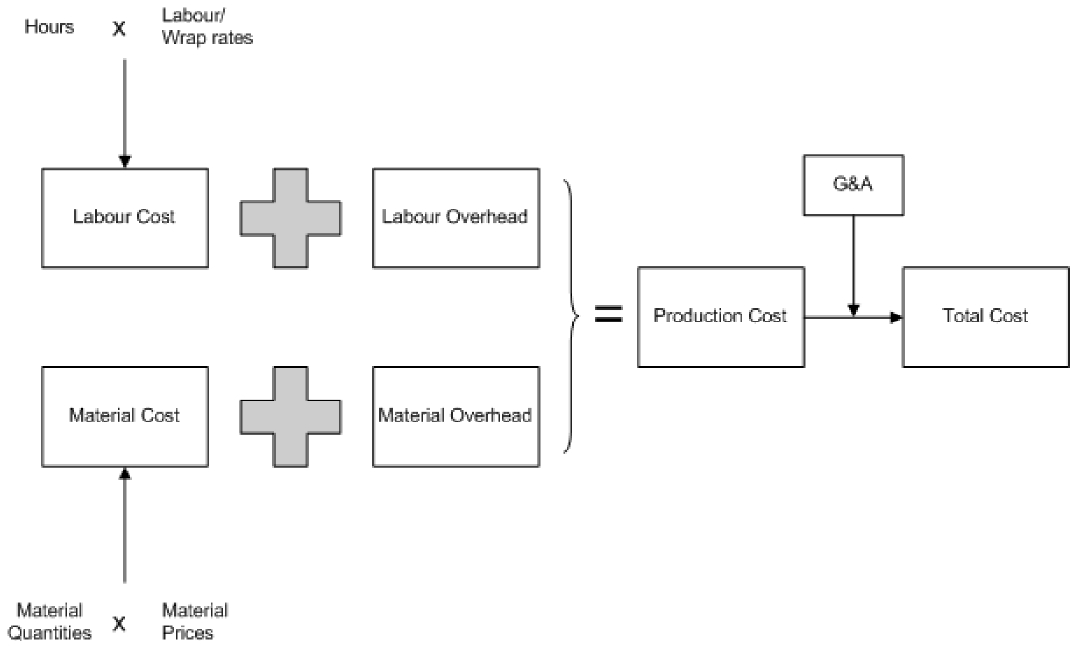


Figure 4.7 – Basic Steps of a Detailed Cost Estimate

Further to the above basic structure, the involvement of the author within the cost functions of the collaborating organisations indicated that they often prefer to split costs into recurring and non-recurring elements.

Upon initial observations, the quality and accuracy of an estimate seems to be related to the current product definition, as well as to the data and information available to the cost estimator at the point of developing the cost estimate. Quite often an estimator would face uncertainties regarding one, or more aspects of the product/project. Due to those uncertainties, the cost estimator would often have to resort in making assumptions in order to compensate for the uncertainty surrounding the inputs at that particular time in the product lifecycle. The amount and level of inputs' uncertainties could be explicitly linked to the stage of the product lifecycle, in which the product is at the point of producing a cost estimate. Once a product definition evolves, and the conditions regarding the production and the overall project become more definite, the amount of uncertainty is reduced. Figure 4.8 graphically depicts this phenomenon.

As described earlier, the uncertainty of inputs is a real hindrance when developing an estimate. In the real world, cost estimators would have to make assumptions whereas inputs may be unknown, in order to account for those uncertainties. In

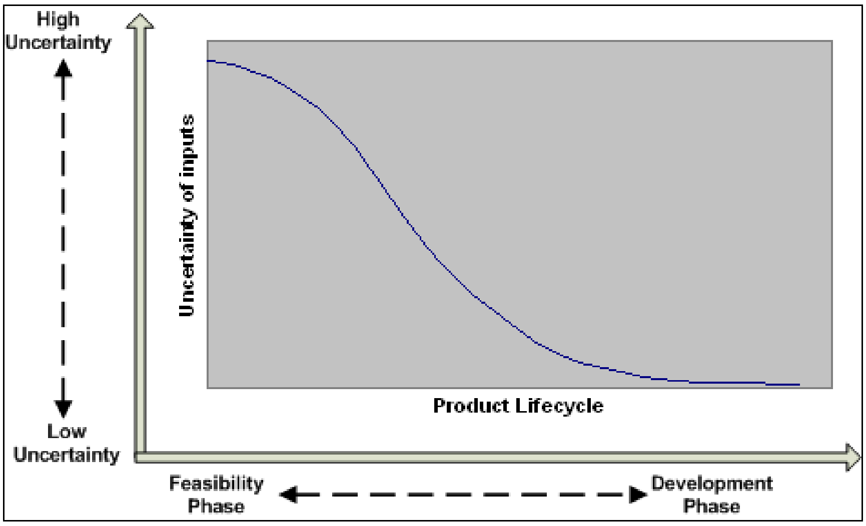


Figure 4.8 – Uncertainty of Inputs Throughout the Product Lifecycle

order to achieve this, the cost estimator relies on knowledge and experience developed through years of direct exposure in the domain. Novices, due to the lack of this expertise, will be unsure as what to do when they face a problem involving uncertainty.

4.1.4 Supplier and OEM Perspectives to CE

The process with which a detailed bottom-up cost estimate is carried out does not vary between an OEM and a supplier. However, what often differs is the purpose for which a cost estimate is produced, and as a result some of its underlying conditions. Suppliers are often referred to as Tier 1/2/3 as a way to classify them within tiers, in order to represent their position in the supply chain. Thus, a supplier may be considered Tier 1 or Tier 2 depending on its position within the supply chain of a particular product. Figure 4.9 depicts a typical relationship between an OEM and its supply chain, and an example of work allocation down the supply chain. It should be noted that a supplier may provide a variety of product(s)/system(s) to an OEM, and at the same time they are going to have a variety of suppliers of their own.

Smaller-size suppliers could be sometimes Tier 1 or Tier 2/3 to an aerospace OEM. However, particularly as far as aircraft systems are concerned (such as hydraulics, controls, and computers), OEMs tend to allocate large proportion of the development of a system to Tier 1 suppliers. They in-turn procure parts from Tier 2 suppliers and

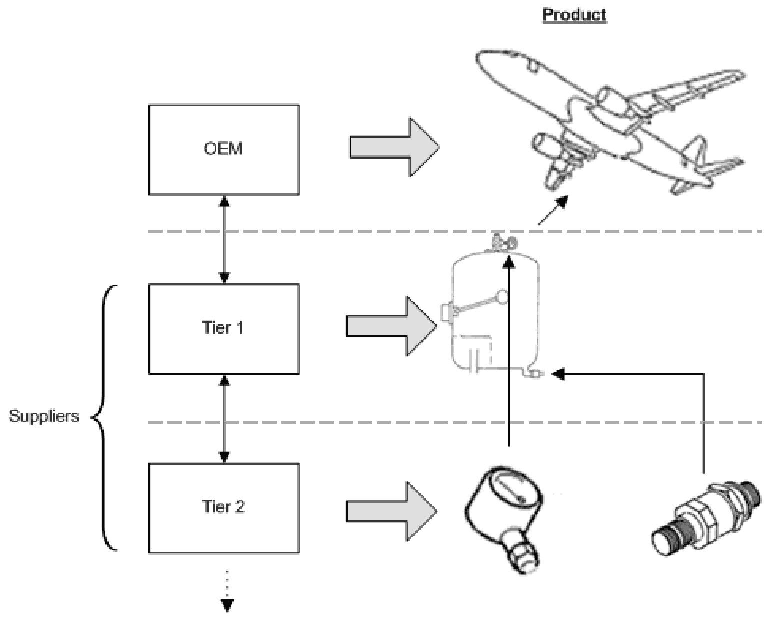


Figure 4.9 – Example of a Typical Supply Chain in the Aerospace Industry

often deliver to the OEM a complete, or a large part of a, system. Small suppliers (which are usually Tier 2/3) very rarely deal directly with the OEM for the procurement of such specialised and critical systems.

For the organisations under study in this research, it was observed that a typical lifecycle for an RFQ, from receiving the RFQ to replying with a complete proposal, varies from 40 to 90 days. This observation is consistent with the observations of Schehr (1989) of 60 to 90 days period for a typical RFQ lifecycle. In general, this period varies depending on the size and complexity of the contract/product, as well as the current market conditions and OEM needs. Figure 4.10 presents the high level actions that take place in a typical RFQ lifecycle. The first three steps upon receiving an RFQ order are according to Schehr (1989) the most time-consuming and are mainly related to functions such as systems engineering, production planning and engineering. It is not until near the end of that cycle that a cost estimator gets involved, since a product definition would be lacking prior to that. The majority of the time is usually spent on activities such as communications with the customer, engineering and other commercial activities (such as pricing, executive board reviews and so on). As a result, only a small percentage of time within this timeframe is often allocated to the cost estimating activity.

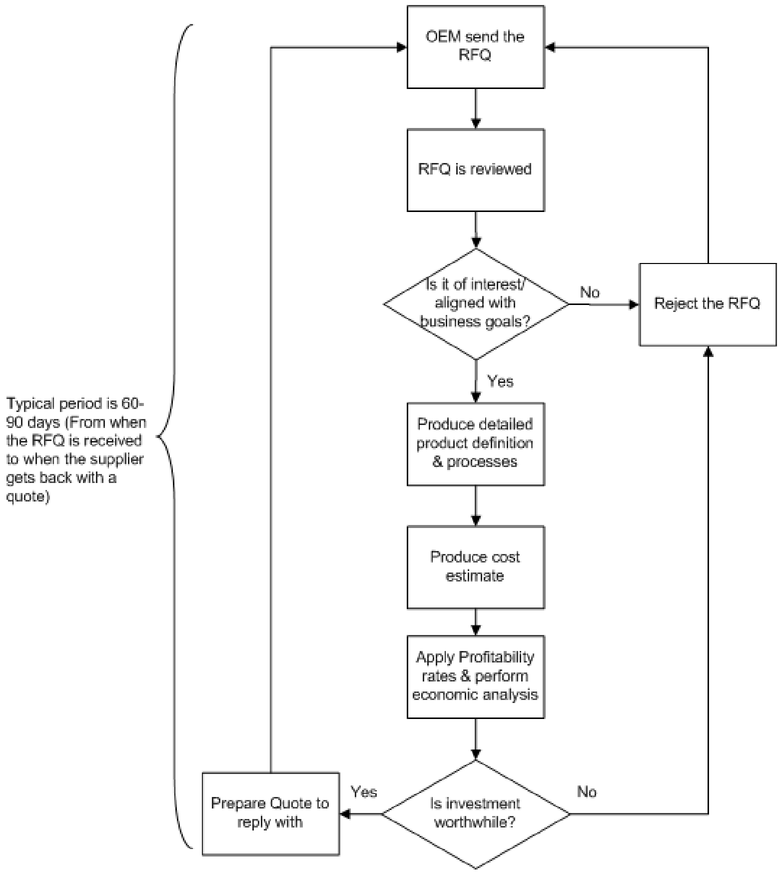


Figure 4.10 – Typical RFQ Lifecycle

Due to the limited time available to produce a cost estimate in the RFQ lifecycle, cost estimators are under pressure to develop their estimates as accurately as possible in a short period of time. The final decision whether to reply to an RFQ, and what to quote to the customer, lies with the management of an organisation. Their decision making, directly or indirectly, is highly influenced by the estimate prepared; and thus the profitability of the prospective work. Their first priority is to identify whether the company will profit from this contract, and then whether the price set (based on that cost estimate) is realistic and competitive in the market. Decision makers expect a high degree of confidence and credibility in the data that they are presented with; it is a cost estimator's responsibility to provide such assurances.

4.2 An Overview of Cost Estimating Knowledge

In Chapter 2, an introduction to the various definitions regarding knowledge was presented based on current literature accounts. The author felt that none of the existing definitions represent accurately the practical knowledge that was identified during the author's interaction with cost estimators at the collaborating organisations. As a result, the author proposes a definition which fully encapsulates what knowledge is within the context of this study. The proposed definition of knowledge was based on the review of the literature, informal discussions and the author's observations, at the research setting(s). The following definition of knowledge is proposed in this study:

> Knowledge is the structured representation of the information that each individual is subjected to, allowing them to make sense of information and particular situations encountered, as well as allowing them to know how to act upon those information (*this structured representation leads to the development of a conceptual understanding of a particular domain*)

Based on the above definition, the author attempts in this Section to provide the reader with a detailed understanding of the knowledge involved in cost estimating and how it is viewed when placed on a wider context. Initially, a high level categorisation of CE knowledge is proposed. Following that, the author describes in more depth how knowledge is viewed in this study, and how 'acquired experience' in a domain imparts on knowledge. Finally, a definition for a novice and expert cost estimator is proposed.

4.2.1 Decomposition of CE Knowledge

Based on the author's involvement in the subject domain and the review of the literature, it was observed that cost estimating knowledge falls into two distinctive categories. The first category involves domain knowledge and the second category involves knowledge regarding the application of the cost estimating practices (more closely related to cost estimating skills). Domain knowledge could be further split into product and company specific knowledge. Figure 4.11 provides a top level paradigm of such a categorisation.

Knowledge of the cost estimating practices can be obtained through training, relevant qualifications and direct experience of applying those CE skills on the job. In contrast, the domain knowledge is difficult to teach and convey from experts to novices. The reason for this encumbrance is that a large part of this knowledge is often tacit and it is a challenging task to externalise. In addition, experts accumulate this sort of knowledge through years of experience in the domain area.

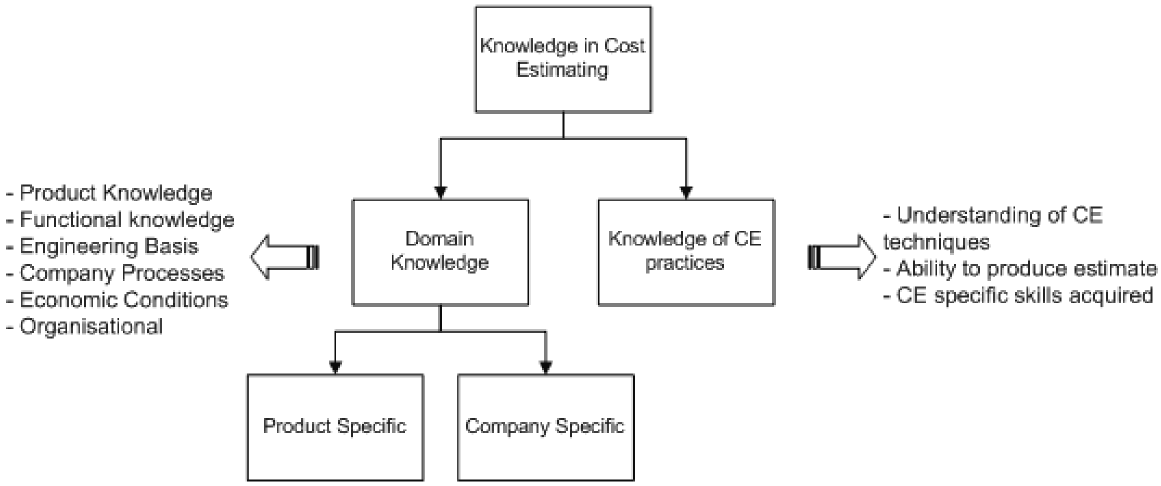


Figure 4.11 – Decomposition of CE Knowledge

Domain knowledge has a larger impact towards delivering a sound cost estimate than knowledge of CE practices. If an experienced cost estimator, who has both experience in the use of CE practices and in the knowledge of domain 'X', is found in another domain (denoted as domain 'Y' for the purposes of this example), s/he would be at loss and there would be a learning curve until s/he develops the expertise required to carry out estimates as good as those s/he would develop while in domain 'X'. The knowledge and skills of the CE practices would remain the same, independently of the domain; however, s/he would face difficulty in understanding and familiarising with the new domain. A familiarisation period would be inevitable, independently of their amount of experience as cost estimators in other subject areas.

Thus, it is of great importance to provide methods and techniques which could enable the transfer and capture of domain knowledge, from experts to novices. As presented in Chapter 2, knowledge and skills regarding the application of CE practices is widely covered in literature and by CE related professional associations. This study focuses solely on the domain knowledge side of CE knowledge. From this point onwards, whenever the term 'knowledge' is mentioned it should be assumed that the author refers to CE domain knowledge, unless otherwise stated.

4.2.2 CE Domain Knowledge based on Experience

The definition of knowledge presented earlier in this chapter relates knowledge to experience, as acquiring knowledge depends on inputs that someone is subjected to. In fact, the Merriam-Webster dictionary defines experience as "the fact or state of having been affected by or gained knowledge through direct observation or participation” (M-W, 2006). Based on the definition of experience one could imply that experience is related to the attainment of knowledge through time; thus, confirming the claim earlier on that domain knowledge is difficult to acquire just through training and the obtainment of qualifications.

Knowledge acquired through experience may take many forms from the quite obvious such as experience on manufacturing processes and product aspects, to less obvious, but equally important areas, such as understanding of how a business operates (and thus expectations regarding the work carried out) and knowing the right people who are going to provide valid and crucial inputs to the estimate. Knowledge about the immediate organisation is quite important and heavily relies on past experience.

Intuition

Cost Estimating is associated with forecasting what the cost of a product is going to be in the future. Even during the later stages in the product development, such as pre-production, there are still quite a few of parameters that are unknown or uncertain up to that point. In addition to the knowledge utilised by cost estimators during the development of their estimate, there is another issue involved; the use of intuition. Jorgensen (2004) has identified that a significant part of the cost estimating process is based on intuition (equivalent to a non-explicit reasoning process). Experts often rely on intuition in order to ‘fill-in’ any gaps at the case where some specific information is not available to them. Intuitive skills are developed by extensive experience in the domain area, being subjected to a plethora of situations; to the point where they have ‘intuitively’ created an understanding of that domain. Intuition is almost impossible to externalise and convey to other people and is only attained through direct participation or observation of a situation, phenomenon or concept.

An example of the application of intuition in a cost estimating scenario is given by the following:

> Cost estimator, Mr. A, has just developed his estimate for a future project and presented it to the project management for review. Mr. A based the estimate on the all the documents supplied by the project manager; ranging from drawings, to a detailed scope of work. The project manager, after reviewing the estimate, identified a cost element, which did not appear in the scope of work or anywhere else in the project definition. He questioned Mr. A regarding that additional cost, thinking that it may be an error from Mr. A’s part.

In the above example, the inclusion of that additional cost element that was not listed anywhere in the project scope, was based on the cost estimator's intuition that there are very good odds that this cost would be incurred; thus, he deemed necessary to include that cost element in the cost estimate. His action was based on years of experience in producing estimates for those kinds of projects. This experience has led him in developing a good understanding of the specialities of projects as such, where he has intuitively developed this skill by observing how projects like that have been carried out in the past.

This study does not attempt to study intuition in any form, but rather present to the reader another dimension regarding human experience in a domain in order to better understand how the intuitive skills of an expert, which have been developed over the years, are directly linked to the tacit domain knowledge required in CE. The development of intuition is linked to one's own experience(s) of a domain (Flyvbjerg, 2006).

4.2.4 Level of Expertise

The identification of CE knowledge and the conceptualisation of the interactions between knowledge, skills and experience led to the definition of the terms of novice and expert. It was deemed important to clearly define how a novice, and/or an expert cost estimator, is viewed in this study in order to avoid any confusion and misinterpretation of the analysis and findings.

In Chapter 2, a review of the literature regarding current definitions of the levels of expertise was presented. In particular, the Dreyfus model of expertise (Dreyfus and Dreyfus, 2005) seems to be widely used and extensive enough to cover the different possible levels of expertise. However, for the purpose of this study, it was decided that such a level of detail in the decomposition of the different levels of expertise was not required. In addition, it was deemed necessary to provide a less generic definition for the two levels of expertise; a definition which is specific to this study and makes reference to CE. The author proposes two CE-specific definitions based on the available definitions in literature and his personal judgement (based on his own involvement within the domain area).

Thus, a novice cost estimator is:

> A recently introduced member to a particular domain. The novice has an understanding of the CE practices and techniques, and/or possesses CE training and qualifications; however, a novice lacks the hands-on experience in that particular domain. A novice has little situational awareness of that domain and minimal discretionary judgement

and, an expert cost estimator is:

> An individual who has spent a considerable amount of time in a domain, and has become proficient in the use of CE practices and techniques throughout the years. An expert has developed an intuitive grasp of situations, and does not any longer need to follow rules and guidelines. An expert has developed a very concise and realistic representation of the domain area, allowing him to take decisions and make assumptions which are of high quality

Throughout this study the author has been essentially acting as the novice, lacking that technical 'hands-on' CE background. The author had a theoretical understanding of the CE practices and a theoretical engineering background, but he lacked the experience and the domain knowledge in the specific area (respectively for each case study in which he got involved with). Novices may typically have less than a year, or not at all, experience in the cost estimation of products in a particular domain.

In contrast, experts in this study were the various cost estimators with whom the author interacted with, from the collaborating organisations. The Experts are proficient in their job and have mastered over the years both the application of CE practices as well as the domain knowledge required in their area. All of the experts, whom the author interacted with during this study, had at least, or in many cases more than, 10 years of CE experience in a particular domain. An expert would possess, amongst others, knowledge of the CE practices, familiarity with the product and domain area, a solid understanding of the manufacturing processes involved and hands-on cost estimating experience within that specific domain.

The following Section presents the work carried out in leading to the identification of the types of CE domain knowledge, as well as the development of a hierarchical classification of the types of knowledge identified during this study.

4.3 Identifying the Types of CE knowledge

In Section 4.1, the CE detailed bottom-up process was modelled. In Section 4.2 the author defined the various terms used in this study and demonstrated his conceptual understanding of knowledge and expertise in the cost estimating subject area. In this Section, the data and information typically utilised in the detailed bottom-up cost estimation of mechanical hardware products, are reviewed. The identification of 'what is needed' in order to carry out a cost estimate, led to the abstraction of 10 main types of domain knowledge present in the cost estimation of mechanical hardware components.

4.3.1 Data Collection

The data collection, leading to the identification of the types of knowledge in CE, involved three main activities. Firstly, the IDEF0 models were analysed to identify what knowledge is required in order to accomplish a particular function of the CE process. Secondly, a number of experienced cost estimators were interviewed and the interview transcripts were analysed for identifying the knowledge needs associated to their everyday job. Finally, the author analysed past cost estimates provided from the collaborating organisations, in terms of data used and information that could be found within them. In addition to the activities mentioned, the author gained a valuable understanding of the knowledge associated to CE through informal discussions with experts in the field and through observation of the domain.

Questionnaire Development

A questionnaire was designed in order to carry out the interviews with five experienced cost estimators, sharing amongst the group an average experience of approximately 22 years. The interviews were semi-structured, allowing the researcher to deviate from the planned questions sequence during the interview in response to other arising subjects. The flexibility of semi-structured interviews often results into the capture of knowledge, not initially thought or intended when drafting the questionnaire. Each interview lasted between 45 minutes to 1 hour and 15 minutes. Table 4.1 provides some background information regarding the experience level and domain of each cost estimator interviewed.

The questionnaire consisted of three main sections; a section focusing on personal interviewee background, the second one on the cost estimating process and the last one on the knowledge within the area of CE. An initial version of the questionnaire was piloted with an expert in the subject, in advance of carrying out the interviews,

Table 4.1 – List of Interviewees

	Experie-nce (years)	Company Type	Position	Background/Domain
Interviewee 1	12	OEM	Principal Cost Engineer	Cost estimation of aircraft systems. Technical and engineering background
Interviewee 2	30	Supplier	Cost Consultant (ex. Commercial Manager)	Cost estimation of aircraft structural parts. Both engineering and commercial background
Interviewee 3	27	Supplier	Head of Cost Estimating dpt.	Cost estimation of mechanical and electrical hardware. Managerial position with a combination of both commercial and engineering background
Interviewee 4	16	Supplier	Head of Production Estimating dpt.	Cost estimation of mechanical and electrical hardware. Strong production background
Interviewee 5	26	OEM	Target Costing Manager	Cost estimation of automotive parts. Both engineering and commercial background

in order to check the questionnaire's effectiveness and fitness for purpose. During each interview hand-written notes would be kept along with audio records in some cases, if permission would be granted to do so.

Once the CE process steps were identified, the questions focused more on what knowledge is required in order to accomplish these steps. An example of the sort of questions included within the questionnaire is presented below. Questions within the second part of the questionnaire aimed towards acquiring a detailed understanding of the cost estimating process itself:

> **Q:** Could you briefly list the steps that you follow during the task of generating an estimate?

While questions within the third part of the questionnaire aimed towards identifying the knowledge required in producing a cost estimate:

> **Q:** While producing an estimate for a specific product what knowledge do you need to have as an estimator, in order to complete the task?

The full list of questions asked during the interviews with the expert cost estimators are listed in Appendix A.1. In Section 4.3.2, the author presents a summary of the responses following the interviews with the five cost estimators.

Analysis of the IDEF0 CE Model

The cost estimating model was analysed in order to identify the data required for carrying out each step of the process. Each function in the model was examined individually, along with its associated inputs, controls and mechanisms. Knowledge relating to the majority of these steps, originated from the interviews which took place, as well as from the author's experience with being immersed in the collaborating organisations' cost estimating departments. Figure 4.12 presents an example of the kind of logic that the author followed in order to carry out the analysis of the IDEF0 models.

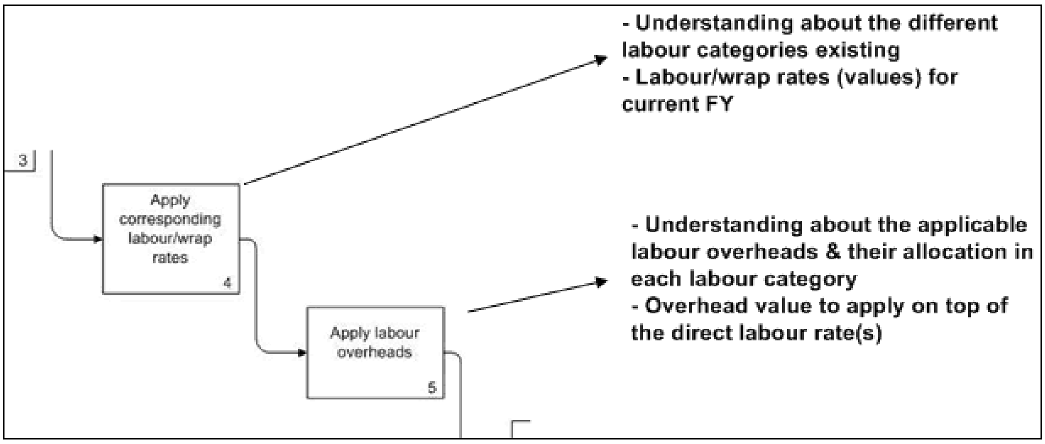


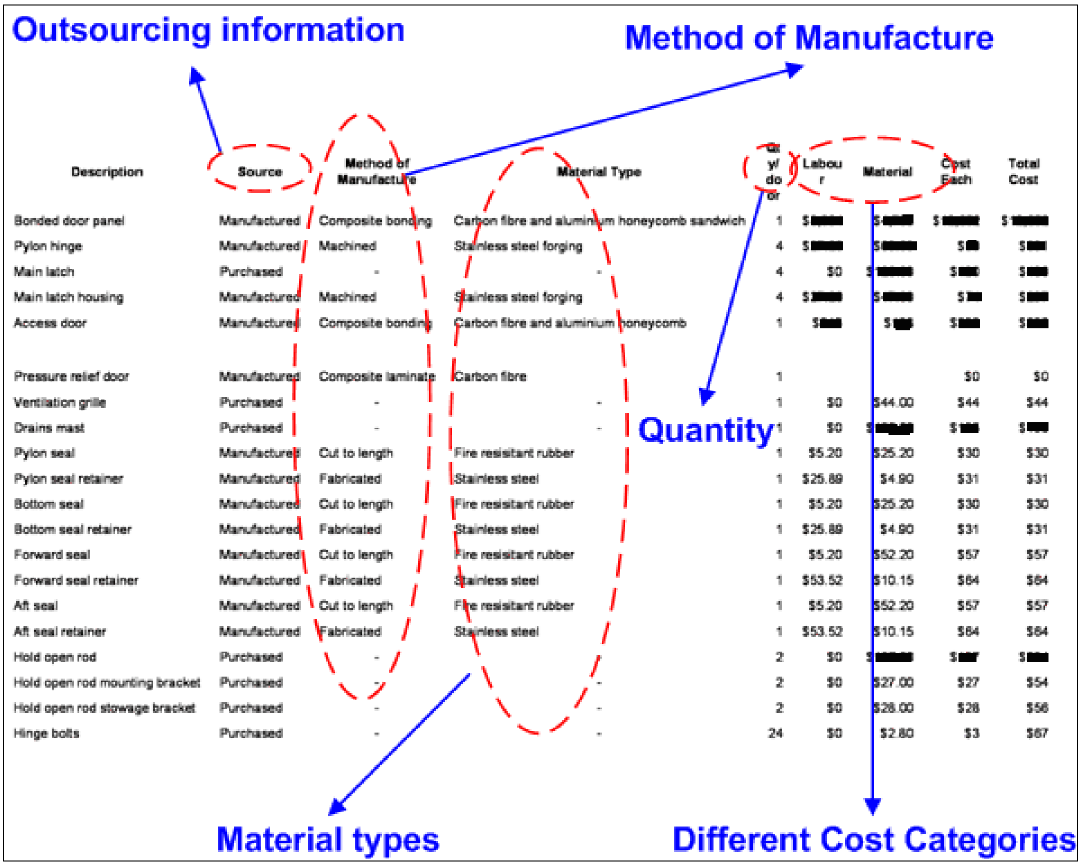
Figure 4.12 – Example of the Analysis of the Cost Estimating Process Model

This process was followed for each step within the model until all the required data and information were identified.

Analysis of Cost Estimates

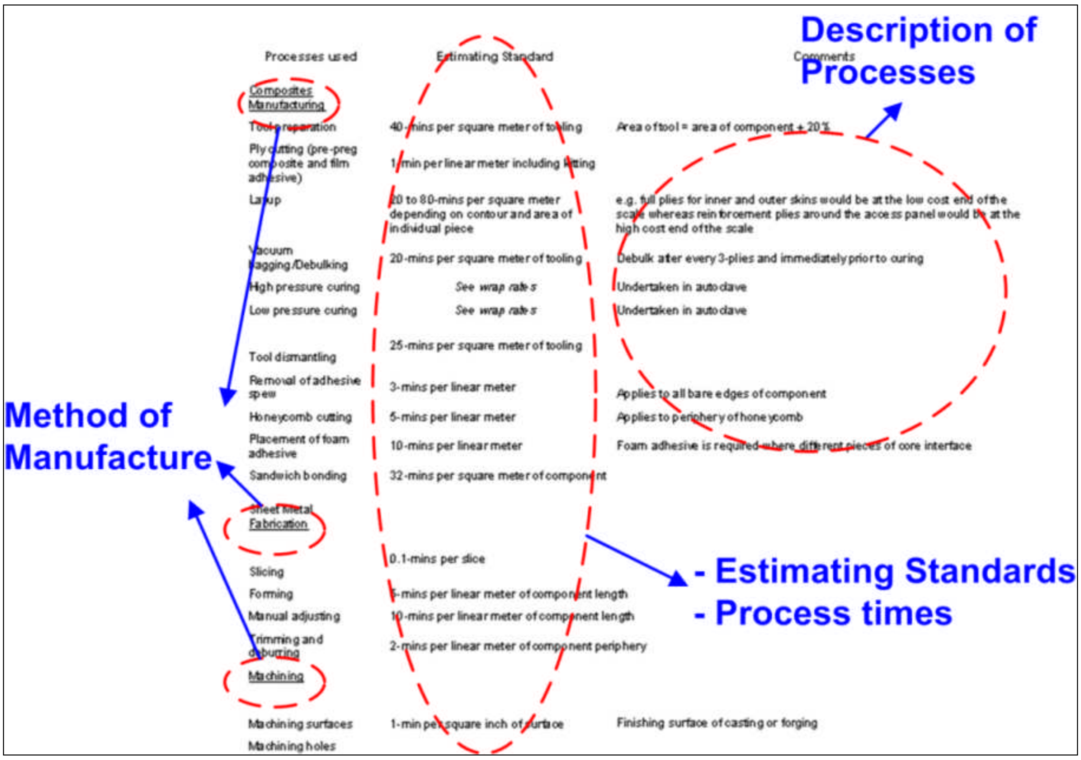
In addition to the interviews conducted and the analysis of the IDEF0 models, a number of past cost estimates were analysed along with their supporting documentation. The estimates were thoroughly reviewed in order to identify the knowledge required in developing them. In some instances past estimates were used to focus the interviews conducted. This technique is called talk-through case study analysis, where a case is used during an interview to prompt an interviewee's memory regarding the knowledge utilised in a past case.

Figures 4.13.(a) and (b) present examples of such knowledge identified through the review of past cost estimates. The markings and notes presented within the figures are similar to the logical process which the author followed.



Description	Source	Method of Manufacture	Material Type	Qty/ door	Labour	Material	Cost Each	Total Cost
Bonded door panel	Manufactured	Composite bonding	Carbon fibre and aluminium honeycomb sandwich	1	[redacted]	[redacted]	[redacted]	[redacted]
Pylon hinge	Manufactured	Machined	Stainless steel forging	4	[redacted]	[redacted]	[redacted]	[redacted]
Main latch	Purchased	-	-	4	$0	[redacted]	[redacted]	[redacted]
Main latch housing	Manufactured	Machined	Stainless steel forging	4	[redacted]	[redacted]	[redacted]	[redacted]
Access door	Manufactured	Composite bonding	Carbon fibre and aluminium honeycomb	1	[redacted]	[redacted]	[redacted]	[redacted]
Pressure relief door	Manufactured	Composite laminate	Carbon fibre	1			$0	$0
Ventilation grille	Purchased	-	-	1	$0	$44.00	$44	$44
Drains mast	Purchased	-	-	1	$0	[redacted]	[redacted]	[redacted]
Pylon seal	Manufactured	Cut to length	Fire resistant rubber	1	$5.20	$25.20	$30	$30
Pylon seal retainer	Manufactured	Fabricated	Stainless steel	1	$25.89	$4.90	$31	$31
Bottom seal	Manufactured	Cut to length	Fire resistant rubber	1	$5.20	$25.20	$30	$30
Bottom seal retainer	Manufactured	Fabricated	Stainless steel	1	$25.89	$4.90	$31	$31
Forward seal	Manufactured	Cut to length	Fire resistant rubber	1	$5.20	$52.20	$57	$57
Forward seal retainer	Manufactured	Fabricated	Stainless steel	1	$53.52	$10.15	$64	$64
Aft seal	Manufactured	Cut to length	Fire resistant rubber	1	$5.20	$52.20	$57	$57
Aft seal retainer	Manufactured	Fabricated	Stainless steel	1	$53.52	$10.15	$64	$64
Hold open rod	Purchased	-	-	2	$0	[redacted]	[redacted]	[redacted]
Hold open rod mounting bracket	Purchased	-	-	2	$0	$27.00	$27	$54
Hold open rod stowage bracket	Purchased	-	-	2	$0	$28.00	$28	$56
Hinge bolts	Purchased	-	-	24	$0	$2.80	$3	$67

(a) – Analysis of an Estimate's Summary Sheet



(b) – Analysis of a Standards Processes sheet

Figure 4.13 – Example of the Analysis of a Cost Estimate

A process as such was followed for analysing the estimate, noting down main categories of data used within the estimate; as well as knowledge utilised by the cost estimator in developing that estimate. As mentioned earlier, the talk-through case study technique was used during an interview with the expert cost estimator. The interviewee would be asked to describe the cost estimate (which s/he had already prepared), in terms of the information and knowledge utilised. The use of this technique provided a form of validating the assumptions made by the author, about the knowledge bundles, and in addition, provided an independent source of analysis; thus reducing the introduction of bias through the author's personal interpretations.

4.3.2 Initial Results & Limitations of Current Processes

As presented in the previous Section, the author carried out semi-structured interviews with five cost estimators. Following the interviews the author analysed the responses in order to identify the current state of the CE processes, as well as the cost estimating knowledge requirements. In Section 4.1.1, the IDEF0 model of the CE development process was presented, which was based on the findings of these interviews. A summary of the responses from the interviews is presented in Table 4.2.

In summary, the cost estimators expressed that a formalised process within their organisations for eliciting knowledge required for developing cost estimates, does not exist. The process is ad-hoc and relies on the cost estimators themselves having the ability and skills in approaching the right Subject Matter Experts (SMEs) for acquiring such knowledge. Thus, there are not any methods or tools that novice cost estimators could utilise, since they lack the experience and knowledge of knowing what they require (in terms of knowledge for developing a cost estimate), and how to acquire such knowledge. The interviewees mentioned that every novice, unavoidably, has to go through a process of learning. If a method could be developed to shorten the period of this process, that would provide value-add to an organisation.

Table 4.2 – Summary of Interviewees' Responses

Que-stion	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5
Q B.3	That will be engineering knowledge, either regarding the manufacturing processes or the design rules driving the configuration of a system. Thus, I need to be able to understand most manufacturing and design issues	RFQ from the customer, general contractual conditions, financial considerations, a good understanding of the manuf. Processes involved, material prices, effort required to undertake various activities, wrap rates, required certification standards, economic conditions, to name a few	Magnitude of the work involved and the breakdown into the effort required by the various departments. A basic understanding of the economic conditions and different types of prices. Prices for materials used, and ability to analyse the sub-contractor costs. Understanding of the production and manufacturing processes; for potentially identifying and areas for cost reduction. Knowledge regarding the learning curve of our production…depends whether we deal with a new product, or a re-run of past ones (for which we are comfortable with). Knowledge regarding the RFQ process (what fees to apply, customer background, contract clauses etc). Understanding of the make-up of the various labour rates and overheads	I need to review the customer requirements, edit and analyse the process plans, and talk with the production leaders to understand how this product will be accommodate into our current production line. Need also to review the RFQ pack to understand the quantities required, and especially timescales (could be a schedule attached). We often use industry metrics for some activities (Boeing is one handbook, with manufacturing standards for example)	Having knowledge about the manufacturing processes involved and the materials used. Understand the production of such parts (how many operators, what kind of capital machinery etc). Be able to apply the various rates and fees. Engineering inputs, from part dimensions, weight, to testing and certification required to meet EU standards. Industry Cost rates. Knowledge of the suppliers and their processes
Q B.4	We do that by capturing them as rules (part of our model)	Yes in terms of how I go about developing a cost estimate. There aren't any practices though regarding the knowledge acquisition	No, to my knowledge	We do this by generating the process plans. Each planner is responsible for a key functional area. We tend to follow the same format & templates. One could potentially retrieve metrics out of these plans	Not specifically; however, recently started to implement a system that would use a standard process, for capturing assumptions within the cost estimate
Q D.2	I would visit the shop-floor and talk to operators, arrange interviews with key engineers, go through the available documentations, and so on	Look into available documentation, read mode about that issue (whether it is books, internet, company publications), identify & talk to experts in that area, review past cost estimates of similar nature	By contacting individuals in the company who may help. Inquire the customer if we need more clarifications. Mainly by making a call or meeting these individuals	Not really. Talk to production engineers, to other planners, or consult the manufacturing standards handbooks as a last resort	*Not answered*
Q D.3	The majority of the case it will be that experts are busy, and difficult to get some of their time	*Not answered*	I am usually aware who to contact. Problems arise when there is missing information from the customer. In that case, I would either ask for further clarifications or make assumptions, and list the assumptions to our submitted price	Unclear customer requirements/specifications	Have to talk with engineers and designers a lot. Main problems have to do with defining the design of the system
Q D.6	A good starting point is to ask people like me, that I could help or point them in the right direction. Talking to the engineers is the best way to understand a process, and be familiar with what is required	Talk to other cost engineers, approach experts in the key areas, go through past estimates and attempt to understand the process and assumptions…difficult to say	Seek help from more experienced colleagues; identify individuals who could help and share the problem with them	Reviewing the handbooks is a point to start. Asking questions to the more experienced colleagues. There is always some period of time involved for junior colleagues to get up to speed	Talk to experts, read more about the subject, identify public sources of knowledge, compared to past cost estimate of similar products

All five cost estimators commented that during the development of an estimate they would have to make a number of assumptions, due to the uncertainty involved. Assumptions and exclusions are listed either within a cost estimate report, or they are attached to the cost estimate.

With regards to the CE processes within the interviewees' organisations, the author identified that there is a lack of any formal methods for assessing the quality of cost estimates. In fact, none of the organisations studied have any methods whatsoever employed within their current processes. Saying that, the cost estimators expressed that they tend to present their work to peers, in order to get feedback, and/or validate the content and assumptions of their cost estimate. This process is currently carried out on an informal basis. Another means of reviewing the soundness of their work is the presentation of their cost estimate and assumptions in executive reviews, where senior level management would typically review their work (mostly at a high level of detail).

Finally, two of the cost estimators commented that the quality of their work is directly proportional to the knowledge on which the cost estimate was based on, as well as the quality in the process followed in developing the estimate. Since cost estimating is a knowledge intensive process, the quality of the process needs to be assured in order to produce a cost estimate of good quality. They understand that there is a lack of methods within their current processes, for assessing the quality of their work, and they could see the benefits of a method that could be implemented within the current CE processes. However, one of the cost estimators mentioned that he does not see this as being a big problem, as far as he is aware of the background and credibility of the individual that carried out the cost estimate, as well as the existence of visibility regarding the process followed in developing the cost estimate. This problem becomes more acute in the case of less experienced cost estimators.

As a result of the limitations identified in the current CE processes, the author proposed a number of points to improve the AS-IS model presented in Section 4.1.1. The comments from the interviews, the author's observations, as well as the concerns that the cost estimators expressed, were considered during the development of the TO-BE process. The TO-BE effectively represents the improvements to the current CE processes, which the author is addressing within this study. Its aim is to address the weaknesses, in terms of quality of the process, that were identified in the current practices. The TO-BE process is presented in Section 4.3.5.

4.3.3 Abstraction to the Types of CE Knowledge

The review of the cost estimating model, as well as the analysis of the interview responses, led to the identification of the various cost elements and the data & information utilised at each step of the CE process. In order to create a useful representation, all the elements identified were classified into higher level categories, based on common characteristics which they may share. These higher level categories are proposed to be the types of domain knowledge required by a cost estimator in order to carry out a detailed bottom-up cost estimate for a mechanical hardware product.

The classification exercise resulted into 10 main types of domain knowledge required by a cost estimator, in order to be able to carry out a cost estimate. The list is not exhaustive; however, the author was led to believe that it fully encapsulates the domain(s) within the cases analysed during this study. At the same time the categories are generic enough, in order to be applicable towards all the cases studied. A description of each type of knowledge identified is presented below.

Product/Functional

It includes any knowledge required by the cost estimator regarding the product itself and its function(s). A description of the product and its parts, and understanding of its functions, an idea of the customer requirements, as well as an understanding of the context of the product (and its lifecycle) are all important for CE.

Design

Design knowledge includes information about the physical characteristics and performance parameters of the product, as well as a good grasp of the product's physical breakdown structure (into its assemblies and components, if any). In addition, a cost estimator needs to have knowledge regarding the design maturity of that product; and more specifically, whether there is any design development effort involved or not.

Production

The cost estimator needs to know the intended production quantity and rate, the use of any special equipment and/or the use of any tooling, jigs and fixtures associated with the production.

Manufacturing

The cost estimator needs to have a good understanding of the manufacturing processes involved in the production of a particular product. In particular, what kind of manufacturing/assembly operations are associated with a particular manufacturing method and a feel of the time taken to carry out these operations. Knowledge is not limited just to a basic understanding of the manufacturing processes, but also being able to apply estimating standards, estimate operation times and be able to apply judgement in any issues related to the production which may not be fully defined at the time of producing the cost estimate.

Additionally, knowledge about the learning curves for the various operations of the production was expressed by some cost estimators to be important to have.

Materials

The cost estimator needs to know the materials involved in the manufacture of the product, typical quantities and prices paid to procure them. It is also desirable to have a basic understanding of those material types' characteristics, and what is the relationship between materials and manufacturing operations associated/required. In addition, an understanding of the quantities required for the manufacture of each part of the product is paramount to the accurate estimation of this part's cost.

Certification Requirements

The aerospace industry is heavily regulated by certification requirements as a means to increase safety and attain a high quality standard of products. The estimator needs to be aware of any special testing procedures required and the quality control activities which need to be undertaken. In most cases documentation (either for certification purposes or to meet some customer requirements) would need to be produced for a produced product; in which case the estimator needs to be aware of the requirements, in order to account the cost of catering for this requirement.

Outsourcing

The cost estimator needs to know whether parts of the product are to be outsourced to external suppliers. In cases where decisions have not yet been made regarding who will be producing specific parts, the estimator would make some assumptions relying on past experiences and current company capabilities. In addition, an appreciation of what it will cost to procure those outsourced parts is required, if vendor quotes are not available at the time of producing the cost estimate.

Contract/Project Conditions

It has been expressed by the interviewees that knowledge regarding the contract/project is very important towards realising the whole picture of a particular estimate; and the conditions of that contract/project provide to the cost estimator a plethora of critical information related to the incurred cost of that product (which is estimated). Knowledge as such includes information regarding the conditions of the agreed contract between customer and supplier, the project schedule and delivery expectations, any other special agreements and the potential risks to the project (which could potentially have an impact on the cost incurred).

Economic Considerations

The cost estimator would need to be aware of the economic conditions surrounding the estimate produced. Economic conditions as such are both internal and external to an organisation. External economic conditions include inflation rates and exchange rates, while internal to the organisation include overhead rates applied (such as G&A), labour rates and any other overheads associated with the production of that product.

Organisational

As a cost estimator it is important to have knowledge of where the data sources are located, who the experts, which could be consulted are, as well as who the stakeholders involved are (both internally and externally to the organisation).

Based on the descriptions of each type of knowledge the author developed a hierarchical representation of those types of knowledge along with a number of examples of their associated information. The proposed representation is exhibited in Figure 4.14 summarising the commonalities found regarding the knowledge associated with the production cost estimation of mechanical hardware, following the various data collection activities.

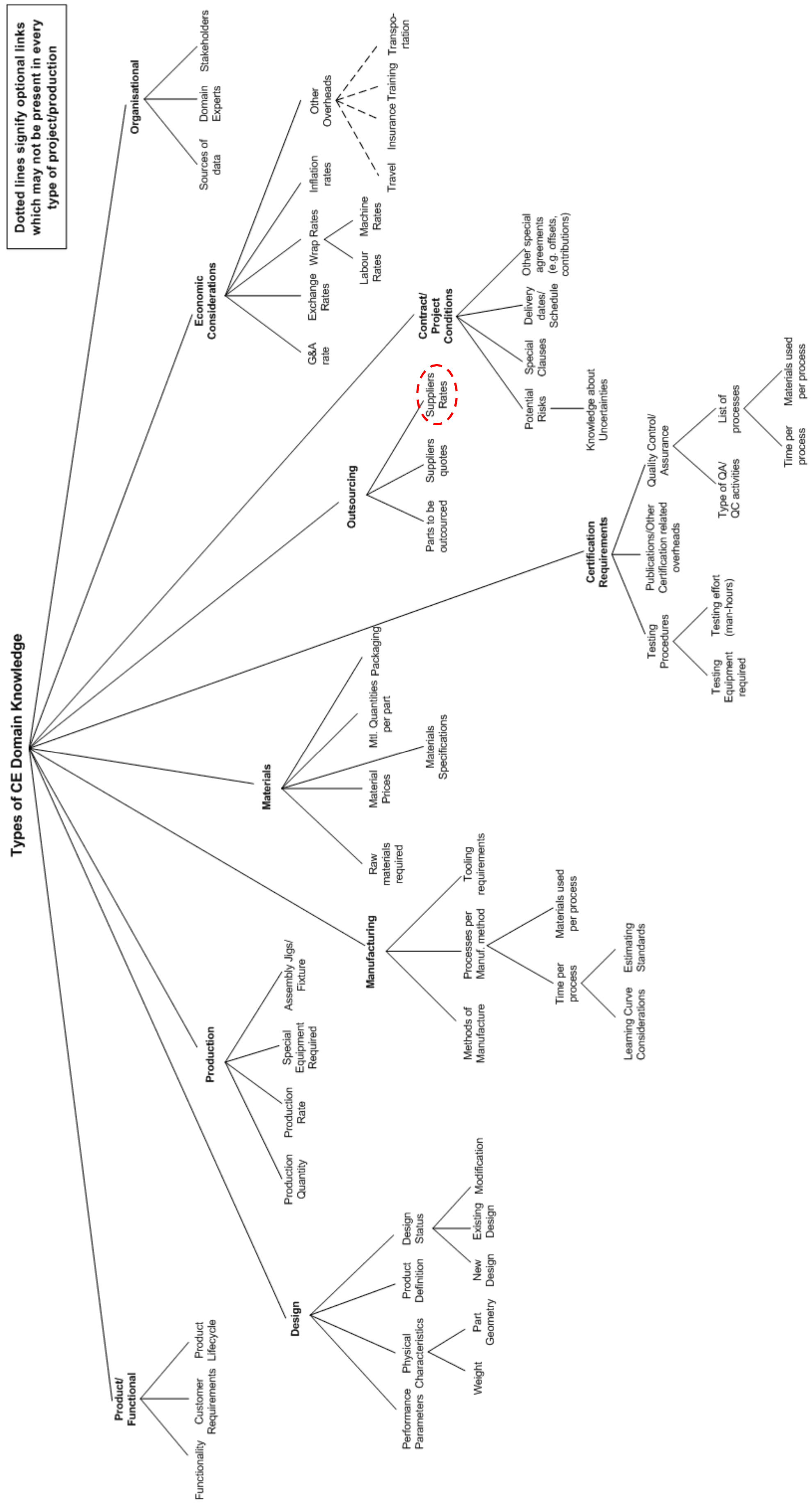


Figure 4.14 – Hierarchical Representation of the Types of CE Knowledge

In the following Section, the author describes the validation process of the resulting knowledge representation, after it was presented to experts.

4.3.4 Validation of Results

The identified types of knowledge, as presented in Figure 4.14, were presented to three experts for validation. Two of the experts are cost estimators in an aerospace organisation, while the third one is a cost estimator for an automotive organisation. The experts were asked to comment on whether they find these types of knowledge representative of their domain, and whether they felt that something was overlooked. It was explained to them that this is a high level representation, and their comments should take that into account.

The experts expressed that they are satisfied with the hierarchical representation and they indeed can relate all the types of knowledge to the everyday line of work. One of the experts felt that under the 'Outsourcing' category, another piece of information could be added. He commented that often in his line of work he would need to be aware of a supplier's rates. This is especially useful when developing should-cost estimates, for components that are outsourced to suppliers. More details regarding his comments could be found later on in this thesis, in Chapter 8, Section 8.3.2.

As a result, the author added this field of information within the hierarchical knowledge structure, as per the recommendations of the expert (highlighted by a dotted line within Figure 4.14).

4.3.5 TO-BE Process

In Section 4.3.2, the limitations of the current CE processes were presented, following the interviews which the author carried out with five cost estimators. In this Section, the TO-BE process is presented, which highlights the proposed improvements to the current CE processes. These areas were highlighted against the AS-IS model, as presented in Section 4.1.1. In addition, the author took into consideration the findings from the literature review, in proposing the improvements in the AS-IS model. Figure 4.15 presents the TO-BE process, based on the high level IDEF0 model of the CE process. The shaded boxes correspond to the proposed improvements.

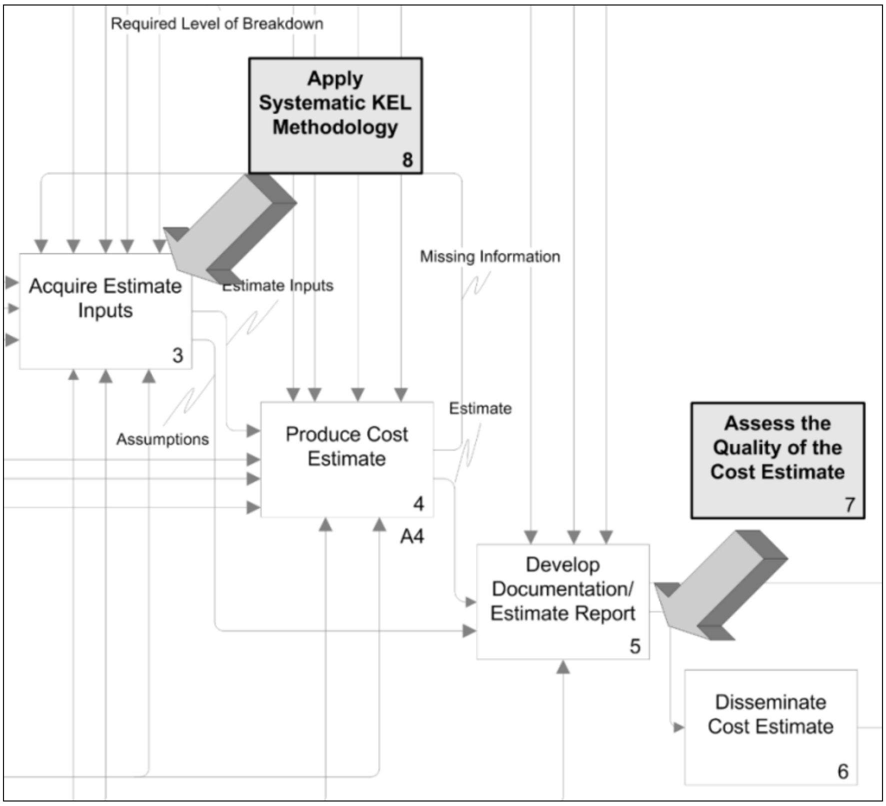


Figure 4.15 – TO-BE Process

There are two main areas of consideration regarding the TO-BE process. Firstly, the author proposes the use of a formal, systematic methodology for eliciting cost estimating knowledge. This process is currently ad-hoc, and as a consequence cost estimators face difficulties in being able to know what knowledge they need to acquire and how. This problem is particularly acute to novice cost estimators. As a result the author proposes the development of a KEL methodology, which would be tailored to cost estimating needs and CE knowledge requirements, and allow cost estimators to elicit knowledge associated with the development of a cost estimate for mechanical hardware products.

Secondly, the author proposes the implementation of a formal method for assessing the quality of cost estimates. As identified in Section 4.3.2, current CE processes lack of any methods as such. The literature findings further confirm this observation, since current methods found in literature for reviewing cost estimates are in the form of simple checklists. It was also observed that some organisations do not even review cost estimates upon dissemination. The author proposes the development of a method for assessing the quality of cost estimate, in a quantitative way; thus, minimising the subjectivity that current methods are plagued with. A method as such could be applied once a cost estimate and its report are completed, in order to assess how good that estimate is. The method should be able to identify areas of weaknesses, in order to guide cost estimators in respect to where the shortcomings of the cost estimate are. The cost estimator would then be able to go back and improve these areas. This process could be iterative until the cost estimator is satisfied with the quality of the cost estimate.

In summary, both processes are highly unstructured in the way they are carried out, subjective and lack of formalisation. By providing a degree of formalisation in both areas, the author believes that the result will be the increase of the quality in the current CE processes. As a consequence, cost estimates are going to be of high quality, if the process followed in developing them has quality embedded into it. The validation of the TO-BE process is partially presented in Chapters 6, 7 and 8 of this thesis.

4.4 The Nature of Cost Estimating Knowledge

As presented earlier within this thesis, the nature of knowledge involved in the cost estimation of mechanical hardware products is multi-disciplinary. There are many types of knowledge that a cost estimator should possess in order to carry out his/her job in an effective and concise manner. In addition, the types of knowledge can also be differentiated in terms of their nature, as well as form that they are usually found under. The aim of this Section is to present the analysis of these types based on their nature, and inherent characteristics, and present a classification of them into meaningful categories.

4.4.1 The Nature of CE Knowledge

Through the analysis of the data and the involvement of the author in the research setting, it was identified that these types of knowledge associated with cost estimating vary in nature. Further analysis of the types of knowledge was carried out by the author, in order to identify the attributes of these knowledge types.

Thus, the types of knowledge were analysed based on the material available to the author both from the interviews and documentation acquired, in order to find their nature. An example of the process followed is the following. An expert mentioned that "…before machining a part, it would require cleaning before-hand". This is manufacturing knowledge, which could be described as explicit. It could additionally be characterised as procedural in nature, and consequently a rule since this step is required to be undertaken before moving to the next step into the production of a part.

Following this approach the author rationalised the various types of CE knowledge identified. Each type of knowledge was analysed in order to identify its nature and inherent attributes. Table 4.3 presents the results of this exercise, where the nature of each type of CE knowledge is presented.

Table 4.3 – The Nature of CE Knowledge

Types of Knowledge	Facts	Casual Knowledge	Explanation	Conceptual	Rules	EJ	Procedural	Justification
Product/Functional	√	√	√					
Design	√	√		√	√	√		
Production	√	√				√		
Manufacturing	√				√	√	√	√
Materials	√					√		√
Certification Requirements	√				√	√	√	√
Outsourcing	√					√		
Contract/Project Conditions	√	√				√		
Economic Considerations	√				√			√
Organisational	√	√						

The knowledge associated with cost estimating was found to consist of various characteristics. The categorisation in Table 4.3 was validated by one expert through an informal discussion. It was identified that typical characteristics of these knowledge types include facts, casual knowledge, conceptual structures, rules, explanations, justifications and procedural knowledge.

In addition, it was observed that the use of Expert Judgement (EJ) is applied within the majority of the types of knowledge associated to cost estimating. The application of EJ includes the use of an expert's rationale, expert decision making and the knowledge is called upon making an assumption. Knowledge as such is in most cases tacit in nature and it relies on a conceptual understanding of a particular domain, which has been developed through years of experience. As a result, novice cost estimators often lack the ability to apply such judgement when faced with solving a problem, since they lack the necessary experience regarding the domain area.

4.4.2 Typical Forms & Sources of Knowledge within a CE Environment

As important as having the necessary knowledge is, knowing where those knowledge assets reside is equally vital. Hamilton and Westney (2002) emphasise that "the Knowledge of who has the information and where to get it, is as important as what to do with the information". As identified earlier in this chapter, CE knowledge is multi-disciplinary in nature and spans across the boundaries of a variety of disciplines.

A significant knowledge source of knowledge is people, who are often characterised as the most valuable asset of an organisation. Experts in a particular area of interest could be engineers, production planners, contracts analysts, financial advisors, procurement and of course cost estimators. As with many disciplines, experienced cost estimators have accumulated a wide level of knowledge throughout the years, which spans into the many diverse areas mentioned earlier. During the interviews it was observed that an amount of this knowledge is tacit in nature and it was acquired through their direct experience with the domain area. Thus, identifying who the experts are is as important as researching documentation and gathering data.

Based on the involvement of the author with the collaborating organisations, and the analysis of the CE process model, a variety of potential knowledge sources were identified regarding the 10 types of knowledge. Table 4.4 provides a list of potential knowledge sources which a cost estimator could consult when looking of a particular type of knowledge.

Table 4.4 – Summary of the Types of Knowledge Identified against Potential Sources

Types of Knowledge	Potential Sources
Product/Functional	- Product Manuals - System Description Notes - Scope of Work - Requirements Document - Proposal Documentation - Experts
Design	- System Description Notes - Specification of Requirements - Drawings - Experts

Types of Knowledge	Potential Sources
Production	- Scope of Work - Programme Schedule - Experts (Production Planners, Project Managers) - Process Plans analysis - Review of past 'similar to' estimates
Manufacturing	- System Specifications Document - Scope of Work documentation - Experts - Process Plans - Estimating Standards
Materials	- Purchasing dpt. - Vendor Quotes - Experts - Document analysis (of similar products)
Certification Requirements	- Certification guidelines - Government/Agencies Directives - Customer(s) requirements - Experts (Contracts, Engineers)
Outsourcing	- Estimate Request - RFQ - Experts
Contract/Project Conditions	- RFQ Document - Draft Contract - Scope of Work - Programme Schedule - Experts (Project managers, commercial dpt.) - Customer(s)
Economic Considerations	- Finance/Accounting dpt. - Inflation tables - Estimate Request - Use of past (adjusted) rates - Payroll slips - Statistics Agencies (Internet)
Organisational	- Experts/Colleagues - Company Intranet - Company documentation

The list of potential sources presented in Table 4.4 is not by any means exhaustive; however, it provides a good basis and direction for a novice cost estimator seeking knowledge regarding a particular subject. Forms, which such knowledge could be found in, include verbal, mind (such as intuition), electronic and/or written.

4.4.3 Multidisciplinary Nature

Following the analysis of the identified types of knowledge regarding the cost estimation of mechanical hardware products, it was observed that knowledge in CE is multidisciplinary in nature. Many of the experts, who the author interacted with, expressed that their profession is multidisciplinary. Therefore, the knowledge that they require to have at hand in order to carry out a cost estimate spans across many subject areas; and it is usually the case where an estimator develops those skills with on-the-job experience rather than previous formal training/qualifications. This is in accordance with observations from other authors (Rush, 2002; Grant, 2004).

CE knowledge relies on a basic understanding of a number of other discipline areas, not explicitly related to cost estimating. As mentioned earlier in this Section, a cost estimator acquires such an understanding either through direct experience in the domain, or the attainment of qualifications and training, or through a combination of both. Discipline areas, as such, are:

- Systems & Design Engineering
- Manufacturing Engineering & Production
- Product Specific Expertise
- Business and Project Management
- Scheduling/ Planning
- Finance/Accounting
- Contracts/Acquisition

These subject areas were identified during the interviews with the expert cost estimators. In their answers, they would often refer to their interaction with various departments within their organisation in order to obtain the necessary information required for their cost estimate, as well as developing an understanding of that subject and its impact on the final cost of the product/project which they estimate for.

4.5 Summary & Key Observations

The work undertaken by the author in exploring the current CE practices was presented; and in particular the cost estimating knowledge needs. Within this Chapter, the author explored the research problem and as a result, identified areas of weaknesses. The findings which emerged out of the author's interaction with individuals within the collaborating organisations formed the basis of describing the current practices; an AS-IS description of the current problems within the cost estimating practices. The author then suggested areas of improvement to the current CE processes, leading to the TO-BE process.

In Section 4.1, the author presented the modelling exercise for the CE process based on his interaction with the collaborating organisations. The purpose of this exercise was to understand how the process currently takes places in industry, as well as to identify what the knowledge requirements in each step of the process are. The following key observations emerged:

- Identified and modelled the CE process; using the IDEF0 modelling technique.
- The time allocated to cost estimators in order to carry out their work is limited and is driven by the dynamic business objectives. As a result, cost estimates are often rushed and do not meet the quality standards that cost estimators would have liked to achieve.
- CE practices between OEMs and suppliers do not, conceptually, vary greatly.

In Section 4.2, the author presented an overview of the CE knowledge based both on the review of the literature and his exposure to the research settings. A decomposition of knowledge into two distinct areas was suggested; domain knowledge and knowledge regarding the practices, respectively. In addition, the author provided a number of definitions to the most commonly used terms and concepts relevant to this study. Key observations included:

- Knowledge regarding the cost estimating practices could be gained through training, qualifications or direct involvement. However, a large percentage of domain cost estimating knowledge is accumulated through experience.
- Novice cost estimators would lack domain knowledge; and experts would be challenged in attempting to pass some of their knowledge to them.

In Section 4.3, the types of CE domain knowledge were identified and presented in a hierarchical manner. In addition, the author suggested potential sources of such knowledge, as well as forms that they typically come as. As a result, a generic hierarchical representation of the types of CE knowledge was developed. In addition, the results of the interviews were presented. Based on the findings of the interviews and the author's observations within the collaborating organisations, a number of observations became apparent, and could be summarised as:

- There is a lack of formalised methodologies which could aid cost estimators in eliciting the required knowledge from subject matter experts.
- Although novice cost estimators could be trained how to carry out their job, there is an issue with their lack of domain knowledge. Such knowledge is developed with experience and takes time to acquire.
- Currently, there are no formal processes within industry that would contribute towards accelerating the learning curve of novice cost estimators, providing them

with a structured guidance with regards to what they need in developing a cost estimate (particularly with respect to domain CE knowledge).

- There is a lack of formal methods for reviewing cost estimates within industry. Currently, the quality of cost estimates is rarely assessed, based on the findings from the interviews.
- It was suggested by one of the interviewees that there is a link between the knowledge utilised in developing a cost estimate, and the resulting quality of that cost estimate.

In Section 4.4, the identified types of knowledge were analysed in terms of their nature and it was found that they do vary, in terms of their characteristics. The key observations that can be drawn from this Section, are:

- Knowledge varies in nature, and as a result the elicitation requirements would vary as well; as suggested by literature.
- Cost Estimating knowledge is multidisciplinary, and spans across many business areas. This is in agreement with evidence presented in the literature.

In the following Chapter, the author introduces the survey study which was carried out in order to identify the inherent characteristics of a good quality cost estimate. The fulfilment of these characteristics could potentially lead to achieving an estimate of good quality. More importantly, a method could be developed, by which estimators would be able to assess the quality of a cost estimate in a quantitative way; thus, minimising the subjectivity that currently surrounds the process of reviewing cost estimates, as identified during the literature review.

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CHAPTER 5 – IDENTIFYING THE QUALITY OF COST ESTIMATES

In Chapter 4, the types of knowledge associated with developing a cost estimate were identified. The author carried out semi-structured interviews with a number of cost estimators within industry, in order to understand what the current practices are. The findings in Chapter 4 showed that there is a lack of formalised processes in terms of identifying and capturing cost estimating knowledge. In addition, the author observed that there is a lack of understanding regarding the required quality of a cost estimate during its development process. Consequently, the current methods for assessing the quality of cost estimates have limitations.

The aim of this Chapter is to explore the perceived quality of cost estimates, and identify the inherent characteristics that a good estimate consists of. As presented in the literature review, since quality is directly related to a set of inherent characteristics, satisfying these inherent characteristics should in theory lead to achieving a cost estimate of high quality. The fulfilment of those characteristics during the development of a cost estimate will also ensure that there is integrity and quality incorporated within the CE process. Thus, in this Chapter, the author investigates the quality through the evaluation of the process used in developing a cost estimate. It is believed that if the quality in the processes is maintained, then that would result in a good quality cost estimate.

However, attempting to define what a good quality cost estimate really is, could be described as a highly subjective process. The use of a survey was employed in order to gain a collective view regarding this subject from a spread of expert cost estimators, and to quantify those perceptions in a constructive way.

5.1 A Good Quality Cost Estimate – A Survey

In this Section, the survey study carried out leading to the identification of these characteristics is presented. A follow-up stage with the survey participants was required in order to identify the weight of the relative importance of each characteristic, contributing towards the attainment of quality in a cost estimate.

5.1.1 Survey Purpose

Upon attempting to define what a good quality cost estimate looks like, it is important to define what quality is, in a generic context. Both the terms of *good* and *quality* are difficult to define due to their highly subjective nature. They mean different things to different people; and indeed, the definition of these terms cannot represent the views of each individual. However, there are some universally accepted definitions, which encapsulate what quality should be considered as. In Chapter 2, it was identified that quality relates to the fulfilment of a number of inherent characteristics. Thus, it is important to identify those inherent characteristics which contribute towards achieving an estimate of good quality. The fulfilment of those characteristics while developing an estimate can ensure that a high degree of quality is embedded within that work. The purpose of the survey was to identify these characteristics and provide the views of cost practitioners about how they perceive a good quality cost estimate.

The use of survey was chosen by the author as the most suitable method for eliciting the opinions of cost practitioners regarding the characteristics of the quality of cost estimates. Selecting a survey, instead of using a workshop or any other data collection methods, has a number of advantages: a) Individuals can be reached from around the world, b) it does not require enormous resources to carry out (compared to interviewing each participant, for example) and c) the researcher does not interfere with the participants of the survey (thus, limiting any bias introduced due to the researcher’s presence).

In the following Section, the process undertaken by the author in designing the survey is presented.

5.1.2 Survey Design

The survey was carried out in two consecutive stages. In the first stage the purpose was to ask the respondents how they perceive a good quality cost estimate. As a result, the questions were ‘open-ended’ giving them the flexibility to answer without being constricted or influenced by the context of the question itself. The results of the first stage were analysed and the characteristics of a good cost estimate were identified.

A follow-up questionnaire was sent to the same list of participants, having a two-fold purpose; firstly, to present the resulting characteristics back to the participants for review and approval, and secondly, to identify the respective importance of each characteristic to the overall attainment of quality in a cost estimate (the corresponding weights of the identified factors).

The overall survey methodology was designed in advance of the survey taking place; by considering the intended purpose and by reviewing relating literature, such as the text of Czaja and Blair (2005), regarding survey design issues. Special attention was given on addressing any issues such as sample selection, analysis of responses and overall survey design considerations. The methodology followed to carry out the survey is presented in Figure 5.1.

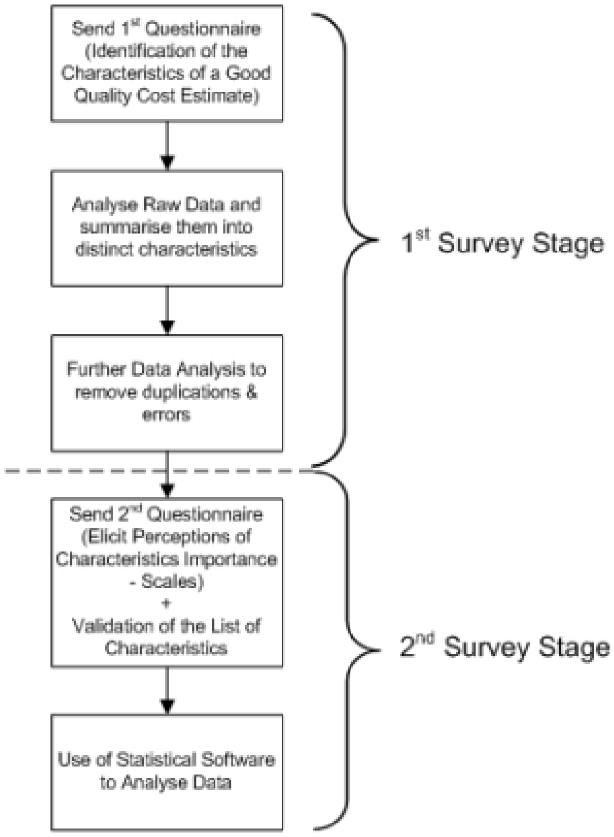


Figure 5.1 – Survey Design

In the following Section, the design of the questionnaires used for the purposes of the survey study is presented.

5.1.3 Questionnaire Design

The design of the questionnaires was carefully planned in advance by reviewing literature sources regarding questionnaires design, as well as testing the questionnaire with at least one researcher before dissemination. A different questionnaire was developed for each stage of the survey. In the first stage of the survey a questionnaire consisting of open-ended questions was developed, while in the second stage of the survey the questionnaire consisted only of scales.

First Stage – Questionnaire 1

In the first stage of the survey the questionnaire was delivered to the participants via electronic-mail. A description of the study, along with the purpose of the survey, was provided at the start of the questionnaire. The questionnaire consisted of two distinct sections.

The first section of the questionnaire consisted of questions regarding background information of the respondents; such as name, location, type of industry and years of cost estimating experience.

The second section of the questionnaire consists of open-ended questions, designed to capture the opinions of the respondents on the subject of quality in cost estimating. The author took the decision not to present at this stage any 'potential' characteristics (of a good cost estimate) as found within literature, in order to avoid introducing any bias to the answers of the respondents. An example of the questions asked is:

Q 2.3: When would you consider a cost estimate to be of good quality? If possible, please list the characteristics that you believe a good estimate should have

Q 2.4: In your opinion, how could one check the quality of a cost estimate? Are there any metrics that could be used, and what should one look for?

A copy of the full questionnaire, as sent to the survey participants, is presented in Appendix A, Section A.2.

Second Stage – Questionnaire 2

The follow-up questionnaire consisted of semantic differential scales, and it was developed on a web page format, using a commercial survey host facility. The participants were directed to the allocated website and rated the scales online. The use of such a tool allowed the researcher to minimise any administration & logistics problems, provide a consistent format, and collect additional information regarding a participant's response (such as time taken to complete the questionnaire, geographical area, and so on).

Figure 5.2 presents an example of a semantic differential scale, showing two of the items within the online questionnaire. The author did purposely not assign any values to the scales themselves; but rather utilised a visual scale. The reason behind this decision was that the aim of the study was to elicit perceptions, and/or feelings, regarding the importance of each characteristic. Thus, it was decided not to assign any values, as per se, in order to avoid introducing any bias in the thought process of the survey participants when it comes to rating the scales.

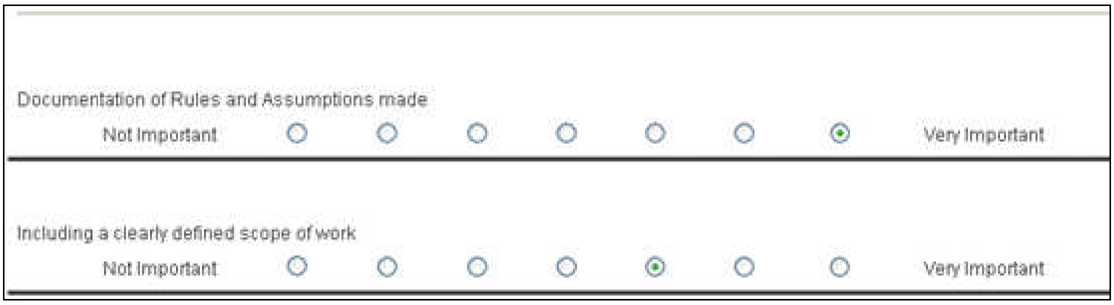


Figure 5.2 – A Screenshot of the Online Survey page; Portraying the Semantic Differential Scales

At the end of the online questionnaire users were encouraged to provide any comments they had concerning the proposed identified characteristics; as well as any other general comments they may have on the subject.

The use of semantic scales to gauge participant perceptions allowed the author to estimate the reliability of the overall questionnaire, as an instrument of data collection. Based on literature accounts, the reliability of a test could be described as "a measure of the correlation between scores on the test and the hypothetical 'true' value" (Norusis, 2000). Cronbach's alpha is a measure of reliability, and more specifically a measure of the internal consistency of the items in the scale (Cronbach, 1951); thus providing a measure of internal consistency for the questionnaire, which consists of a number of items. The coefficient alpha (α) was calculated as .91 for the questionnaire (29 items). Crobach's alpha values typically range from 0 to 1, and the closer the alpha coefficient is to 1, then the greater the internal consistency of the items in the scale is. According to Norusis (2000), an alpha coefficient greater than .80 signifies a good scale.

5.1.4 Target Audience – Sample Selection

The survey targeted cost practitioners with, at least, a few years of experience from a variety of industry domains and geographical locations. The author took into account Robson's (2002) consideration to focus not only on the response rate but also on the representativity of the sample. According to Cook *et al.* (2000), in a survey research the response representativeness is more important than the response rate.

It was decided to send the questionnaire to a pre-defined list of individuals who are known to be cost practitioners, rather than mass-email the questionnaire to a larger number of people who may not have the required background or experience in the subject area. The identification of such individuals was based on contact details provided through Cranfield University, as well as on the author's professional contacts from the cost estimating domain.

The initial questionnaire was sent to a sample of 63 individuals through electronic-mail; all of which have been known at the time to be experienced cost practitioners. An introductory letter was provided requesting their participation in this study, as well as introducing the overall purpose of the survey. Following a preliminary analysis of the answers of the respondents, it was found that the usable responses, found to be 'fit' for analysis, amounted to 26 fully completed questionnaires. This amount exhibits an estimated response rate of 41%, which is particularly high for this type of survey.

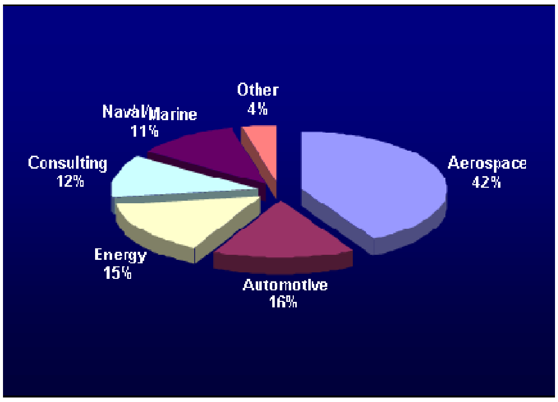
5.2 Identifying the Characteristics of a Good Quality Estimate (1st Survey Stage)

In this Section, the first stage of the survey study, which led to the identification of the inherent characteristics of a good quality cost estimate, is presented. The identification of these characteristics was based on the views expressed by the participants of this survey study. Their views are based on years of industrial experience in the subject area.

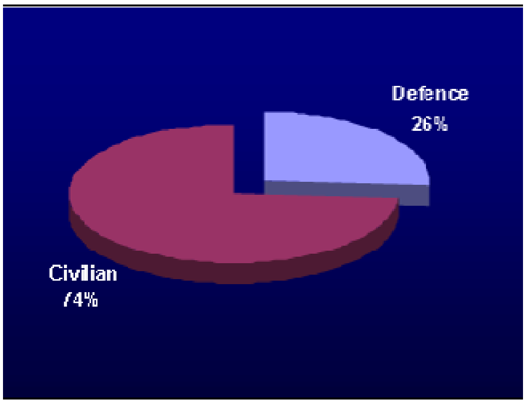
5.2.1 Respondents' Profile

The highest percentage of the respondents is coming from the aerospace industry and accounted for the 42% of the overall sample. The rest of the industries represented are, the automotive industry with 16%, the energy industry (nuclear, oil

& gas) with 15%, the consulting sector with 12%, the naval/marine industry with 11% and finally the heavy machinery industry with 4%. The majority of the participants who took part in this survey are coming from the civilian industry sector, with only 26% of the sample working for, or being directly related to, the defence sector. Figure 5.3 graphically presents the survey respondents distribution based on industry (a) and sector (b).



(a) Industry Distribution



(b) – Sector Distribution

Figure 5.3 – Respondents Distribution Based on Industry & Sector

The survey participants were asked to state their experience, in years, in the area of cost estimating. Table 5.1 presents the various levels of experience within the sample. It has to be noted that 81% of the sample consists of experienced cost estimators with a lot of years of hands-on industrial experience. The sample represents a good experience distribution, from junior cost estimators to highly experienced ones.

Table 5.1 - Sample Distribution based on the Participants' Experience in Cost Estimation

Groups (years of experience)	Number of Participants	Percentage of overall sample	Mean (years of experience)	Standard Deviation
3 – 6	5	19.23%	4.8	1.3
7 – 11	4	15.38%	10.0	0.8
12 – 20	6	23.08%	18.8	1.7
21 – 25	4	15.38%	24.2	1.5
26 and over	7	26.92%	31.4	2.1

The cost estimators who took part in this survey came from a variety of geographical locations. Participants from the United States accounted for the 12% of the sample, with the remaining 88% coming from Europe. Participants coming from the United Kingdom accounted for the 76% of the whole sample.

5.2.2 Survey Results

In this Section, the results of the first stage of the survey are presented. The results represent the answers of the survey participants to the various questions regarding the quality of cost estimates.

Cost Estimate Types and Techniques Used

Table 5.2 presents the answers of the participants, when asked to state what types of estimates they usually carry out in their everyday job. It should be noted that cost estimators may usually carry out, as part of their job, a number of different types of estimates. Thus, the percentage values presented in Table 5.2 represent the number of the participants that stated to predominately carry out this type of estimate, out of the total number of participants in this survey.

Table 5.2 - Types of Estimates Carried out by the Participants

Type of Estimate	Percentage of Participants
Rough Order Magnitude (ROM)	53.85%
Bid & Proposal Analysis	50.00%
Should Cost	42.31%
Budget	30.77%
Fixed Price Estimates	19.23%
Supplier Evaluation	15.38%
Value Engineering & Value Analysis	7.69%
Trade Studies	3.85%
Other	11.54%

The participants were asked to state which estimating technique they usually utilise to carry out their estimates. The detailed (bottoms-up) technique was mentioned by 84.6% of the participants, and it is the most widely used cost estimating technique. The analogy technique was mentioned by 57.6% of the participants. The parametric technique achieved a similar percentage value, while the Activity Based Costing technique was mentioned only by 11.5% of the participants.

The Characteristics of a Good Quality Cost Estimate

The participants were asked to list the characteristics, which they believe to define a cost estimate of good quality. The answers of the participants to the open-ended questions were reviewed and sorted based on their similarities, differences and uniqueness. Each individual point was noted down, for all participants. At the end of this process it was identified that a number of participants would mention the same point, so similar answers were grouped together. Table 5.3 presents the characteristics which were identified by the participants.

Table 5.3 – The Initial 24 Characteristics of a Good Quality Cost Estimate (Pre-Analysis Results)

	Characteristics
1	Documentation of Rules & Assumptions
2	Full breakdown (incl. labour, BOM, sub-contractor involvement)
3	Shows clearly defined Scope of Work/Specs
4	Use of risk analysis (cost sensitivities due to risk) - probabilistic estimate
5	Simple & Clear Presentation of results (clarity)
6	Shown within the estimate a relationship to schedule
7	Accuracy in-line with business need
8	Based on a 'similar to' product (use of actual known costs - sanity check)
9	Based on valid quotes for purchased content
10	High level of technical detail
11	Consistency
12	Repeatable
13	Documentation of Data Sources
14	Supplier (or other parties) buys-in the model
15	Formal Structure - followed a defined process to generate the cost estimate
16	Reliable data sources (accurate & up-to-date data)
17	Manufacturing quantity & rate
18	Economic period of costs
19	Estimating method appropriate to final use of estimate - (effort spent to create an estimate)
20	Documented Basis of Estimate (BOE)
21	Benchmarked in the industry
22	The Cost Estimate summarises the Main cost elements
23	Identification of cost drivers (for cost reduction purposes)
24	Estimate is delivered on time

Twenty-four characteristics were identified by the participants. Documentation is one of the characteristic that was mentioned by the majority of the participants in this survey, as being paramount towards a good quality estimate. Other characteristics refer to the use of risk analysis, a clear presentation of the estimate and the results, the level of accuracy based on the business need and the transparency of the cost estimate. In general, the characteristics that were identified cover all aspects of the cost estimate development; from the estimate itself and its background data and conditions, to documentation, risk analysis and validation.

In addition, the participants were asked to list the metrics, which they believe could be used in order to measure whether a cost estimate is of good quality, or not. Table 5.4 presents the metrics which were identified by the survey participants.

Out of the 16 metrics identified some of them are quantitative in nature, such as checking estimate accuracy with actual costs, checking against other

Table 5.4 – The 16 Metrics Identified by the Cost Estimators (Pre-Analysis Results)

	Metrics
1	Use Actual from similar programs/parts - historical data
2	Calibrated to company processes/rates
3	Check accuracy (against actual cost)
4	Benchmarking & Market test studies (and/or compare with vendor quotes)
5	3-point principles (check with other cost estimating methods)
6	Credibility of Source data (also check quality of information/knowledge used)
7	Check consistency - consistent formal approach
8	Check auditability
9	Let expert(s) validate major assumptions made
10	Gauge how the supplier responds to the estimate
11	Metrics such as cost divided by weight
12	Access to the Basis of Estimate
13	Check whether other areas of the business have contribute to the estimate
14	Check assumptions made (logic, realistic and basis)
15	Maintain estimate snapshots throughout lifecycle of product
16	Allow peer review

estimates/models and compare estimated costs with market alternatives. Some others are qualitative in nature, such as gauge how the supplier responds to the estimate, review the assumptions made, check the consistency of the estimate and check the quality of supporting documentation. Qualitative metrics, as such, are difficult to use in-practice while reviewing cost estimates, and solely depend on the subjective interpretation of the individual who applies them.

Upon initial observation, some of the characteristics are similar in nature and context when compared to some of the metrics, and vice-versa. Combining the two together resulted in a list of 40 factors which could potentially be used to assess the quality of a cost estimate. Based on the objective that the final list should contain factors which could be used to review cost estimates, a further analysis was undertaken to filter down these into a final 'usable' list, which would not include any repetitive factors. The further analysis of the initial results is presented in the following Section.

5.2.3 Further Analysis of Initial Results

The following step in the analysis of the survey results was to go through the list of factors and find any repetitive, or closely related to, concepts. Such factors would be merged or excluded. Due to the 'open-questions' nature of the questionnaire used during the first stage of the survey, some respondents often used the answer-fields to describe their thoughts; quite often diverting from the question's specific context. Thus, it was deemed necessary to 'scrub' these answers and filter out any irrelevant concepts deviating from the scope of the survey's subject.

Following the initial analysis of the data, the author realised that although questions 2.2 and 2.3 of the questionnaire were different, they were essentially asking the same thing. It was observed that the characteristics of a good quality cost estimate could at the same time be metrics for assessing quality. This was also reflected in the replies of the participants, where similar replies were given against these two questions. For example, a participant would identify a characteristic of a good quality estimate as 'reliability of data & sources', and would provide a metric as 'check the reliability of data & sources'.

As a result, a filtering exercise was carried out which resulted in a final list of 28 characteristics which could potentially be used to check how good an estimate is. This process was carried out by the author based on a list of requirements and criteria. The input of an expert in the domain area was also utilised to check some of the assumptions made and ensure that the rationale applied is valid. As a final measure, in order to validate whether the final list of factors is representative of a good quality cost estimate, the final list was sent back to the survey participants for feedback and validation. The participants were asked to review the final list of characteristics, which they were eventually going to rate, and at the end provide any comments based on whether they agree with the list presented.

The selection exercise, and the exclusion of certain factors, was based on the following criteria:

- The exclusion of any factors which are similar in meaning/context; and if applicable, merging of factors which are similar
- Exclusion of any factors which are too generic in nature, and thus could not possibly be used in assessing a cost estimate

Table 5.5 presents the list of 11 factors that were excluded and the rationale for doing so.

Table 5.5 – Factors Excluded Following the Filtering Process

Factor	Reason for Exclusion - Rationale
Check accuracy	Repetition - Merged with the 'accuracy in-line with the business need'
Access to the Basis of Estimate	Repetition - It has already been covered by the characteristic 'Documented Basis of Estimate'. If a BOE is documented and provided with the estimate, it is logical that there is access to it
Check auditability	Too generic - Additionally, it is not possible to check whether a cost estimate is auditable without auditing it in the first place.
Repeatable	A minority of respondents mentioned the term 'repeatable'; referring that the estimates and methods should be repeatable. This could not possibly be checked at the time of assessing the quality of an estimate, thus it has been eliminated from the final list
Consistency	Too generic. It is not possible to define what the estimate should be consistent to (as one would need some clear & specific reference points; and additionally each case studied would have difference reference points), let alone assessing consistency as an attribute in itself
Check consistency - consistent formal approach	Similarly to above – The 'formal approach' part is already addressed by the characteristic 'Following a (pre)defined process to generate the estimate (such as dpt. procedures)'
Maintain estimate snapshots throughout lifecycle of product	Although a valid observation, we should be able to review a cost estimate on its own (as quite often in industry an estimate is 'stand-alone' and there won't be any trail throughout the product lifecycle)
Metrics such as cost divided by weight	Too specific for particular applications and needs - In addition, it could be merged to the characteristic 'check with other cost estimating methods', as they share the same underpinnings
Check assumptions made (logic, realistic and basis)	Repetition - Merged with the 'let expert validate assumptions made'. An auditor may not have the knowledge to check the logic and basis of assumptions. An expert validating them, implies that they are realistic and based on logic
Credibility of Data Sources	Merged with 'Reliability of Data Sources', since they have are similar in nature. Now presented as 'Credibility and Reliability of data sources'
Gauge how the supplier respond to the estimate	Repetition – Equivalent in context to the 'Supplier buys-in the process/model'

The final list of the 28 characteristics, derived following the analysis of the initials results, is presented in Table 5.6. It has to be noted that an additional characteristic was excluded from the final list, following the results of the statistical analysis. Following the second stage of the survey it was identified by the cost estimators that the characteristic 'estimate is based on similar to products – use of actual/historical data' was the same with the 'Estimate, or part of it, can be checked against a known cost (for example, a past 'similar to' estimate)' characteristic.

Following the comments of the survey participants, the author carried out a correlation analysis to find out whether these two characteristics have indeed attracted similar ratings. The results of this analysis are presented in Section 5.3.5.

Table 5.6 – Final List of the 28 Characteristics of a Good Quality Cost Estimate

	Characteristics
1	Documentation of Rules & Assumptions made
2	Including a clearly defined scope of work
3	Simple and Clear presentation of results
4	Supplier (or other interested parties) buys-in the process/model
5	Estimate is based on high level of technical detail
6	Identification and evaluation of potential risks (risk analysis included with the estimate)
7	Estimate updated for economic period
8	Identification of cost drivers (for cost reduction purposes)
9	Estimate is delivered on time
10	Documentation of data sources
11	Estimate based on valid quotes of purchased content
12	Peer reviewed
13	Assumptions made have been validated by a subject matter expert
14	Credibility and Reliability of data & information sources (whether the sources are people or databases/documents)
15	Following a (pre)defined process to generate the estimate (such as dpt. procedures)
16	Estimate/model calibrated to company's processes/rates
17	Awareness of the manufacturing quantity and production rate(s)
18	Accuracy (specific to the type of estimate/business need)
19	Estimated cost benchmarked against industry norms (e.g. carrying out a market study of similar products)
20	Provision of a Basis of Estimate (BOE) with the estimate
21	Use of additional cost estimating techniques for the purposes of cross-check; or even check the estimate's output against an existing calibrated/proven cost model
22	Estimate, or part of it, can be checked against a known cost (for example, a past 'similar to' estimate)
23	Estimate summarises main cost elements (breakdown into the various cost elements such as, labour, materials, sub-contractor involvement and so on)
24	The choice of estimating method (and the effort spent) is appropriate for the final use of the estimate
25	Provision of supporting documentation/report (covering every aspect of the estimate) – (relating to transparency)
26	Shown within the estimate a relationship to schedule
27	Have other areas of the business contribute to the estimate (e.g. inputs from Finance, Operations and so on)
28	Completeness of the WBS/PBS/CBS of the estimate (how well defined it is for the type of the estimate carried out)

The following step in the analysis was to find out whether this list had captured all the factors that the survey respondents believed to be important towards achieving a good quality estimate. In order to validate the final list, during the second stage of the survey the list was forwarded back to the respondents. The main purpose of the second survey stage was to identify the relative weight of each characteristic against the overall estimate quality; however, the respondents were also asked to review the list and comment on whether they disagree with its content, and whether they believe something was excluded. The second stage of the survey is presented in Section 5.4.

In the following Section, the author presents a discussion of the results and a commentary regarding the survey participants' comments on the topic.

5.2.4 Discussion of Results & Additional Comments regarding the Quality of Cost Estimates

The identified characteristics are based on the survey participants' perceptions as to what are the characteristics that a good quality estimate should consist of. A number of characteristics within the list are also identified as *best practices* by the study of Hamilton and Westney (2002), as presented in the literature review. These are the 'inclusion of a clearly defined scope of work', 'estimate is based on similar-to products', 'estimate summarises main cost elements (sufficient breakdown)' and 'estimate is updated for economic conditions'. Overall the results did not come as a surprise since they could be described as 'common knowledge' to any cost estimator; required in order to generate cost estimates of good quality. It has to be noted that a large proportion of the participants identified that delivering an estimate on time should be a measure of how good a cost estimate is (and thus, effective in its final use at that point in time). Additionally, the cost estimators expressed that good cost estimates should present a clear relationship to the schedule.

It was also observed that a number of the identified characteristics are related to the knowledge required in developing a cost estimate. Some examples of such characteristics include the 'estimate based on a high level of technical detail', 'estimate is updated for economic period' and 'estimate calibrated to company processes/rates', to name a few. All these areas require the utilisation of CE knowledge by the cost estimator. So, the quality of a cost estimate partially relies on the knowledge utilised in developing that estimate.

Since the survey targeted a wide range of cost estimators, coming from a variety of industries, using various cost estimating techniques, then the results could be assumed to be representative of cost estimates in general; not constrained by industry, estimate purpose and cost estimating technique used. This assumption was tested during the second stage of the survey by comparing the perceptions of various sub-groups within the sample in order to explore whether there are any major differences in perception patterns. Thus, this constituted a way of verifying this assumption; the results of which are presented in Section 5.3.5.

Participants' Additional Comments

In addition to the answers to the specific questions found within the questionnaire, the author wanted to gather the estimators' general comments regarding the subject area. As a result, there are a number of comments that were expressed by the participants of the survey. A selection of them is presented below:

"A good estimate is an estimate that you trust enough to move forward to the negotiation table". This comment essentially implies that all parties are content with the estimate and consider it good enough to place confidence upon it and enter negotiations with potential customers and/or suppliers.

"An estimate needs to be flexible to enable other opinions and updated knowledge to be utilised". As identified from the interviews in Chapter 4, the knowledge utilised by cost estimators is crucial in developing a good cost estimate. It is often the case in industry that cost estimates are constantly updated, during the product lifecycle, in order to reflect the latest information and conditions surrounding the assumptions within the estimate.

Regarding the use of a 'well defined WBS/PBS' an estimator commented that: "Many parametric and analogous estimates do not have a well defined WBS, but are nevertheless useful and 'good' ".

"A good cost estimate requires quality data; however, even a very rough estimate may be considered 'good' if it delivers to the client's expectations". This comment again highlights the relationship between the quality of data & information utilised and how good the estimate is. It also addresses the point mentioned earlier that the final estimate purpose has a leverage on the estimate make-up, as well as the expectations and needs of a particular business.

Finally, a number of the respondents commented on the weaknesses of the current processes that they utilise in reviewing cost estimates, and especially the subjective nature of this activity. They commented that any formal methods, which could reduce the subjectivity and bias involved in reviewing cost estimates, would add credibility to their work and increase confidence in their processes, as well as contributing to the formalisation of their current practices.

Some Thoughts Regarding Estimate Accuracy

It was presented in the literature review that many authors associate accuracy with good estimating. However, only a handful of cost estimators actually mentioned accuracy as a characteristic of a good quality estimate. Actually, whenever accuracy was mentioned as a characteristic of a good quality cost estimate, it was under a different context, compared to just being accurate to an actual cost. It was more inclined towards the concept of generating estimates, accurate enough, in fulfilling a business need/purpose at any point in time.

Participants seemed to imply that checking the accuracy of a cost estimate against actual(s), and thus relating this to how good that estimate was, is a kind of misleading practice. The reason could be that the underlying conditions, assumptions or situations may be different between the current estimate and the historical costs. It was expressed by a number of the participants, that what is more important is the level of accuracy depending on the specific estimate purpose at that point in time, as well as a solid understanding of the underlying conditions that led to an accurate or inaccurate estimate in the first place. In addition, time is a critical factor in developing cost estimates, as well as taking decisions based on them. Whether a cost estimate is accurate or not does not become apparent until much later in the project lifecycle. By that point in time, decisions have already been taken and a cost estimate has already served its purpose.

5.3 Elements Weights Identification (2nd Survey Stage)

As a result of the survey carried out, a number of characteristics were identified, believed to contribute towards a good quality cost estimate. The analysis of the data collected resulted in the identification of 29 inherent characteristics. As presented earlier in Section 5.2.3, once characteristic was excluded following the analysis of the results of the 2nd stage of the survey; thus, resulting in the final list of the 28 characteristics as presented in Table 5.6. A decision was taken that a follow-up session was necessary due to two reasons: 1) for the survey participants to validate the list of the 29 characteristics, and, 2) to identify the relative importance of each characteristic on the overall estimate quality.

5.3.1 Proposing a Method for Quantifying an Estimate's Quality

Determining how good an estimate really is, should be a combination of a variety of factors. A hypothesis put forward was that quality could be an attribute that all these factors relate to. The effect of satisfying those factors could potentially lead to achieving high quality, in the estimating task at hand. Thus, with quality as the dependent variable, equation (1) is proposed as a means of measuring quality (Q) in a quantitative way.

$$Q_{rated} = f_1 * w_1 + f_2 * w_2 + \ldots + f_k * w_k = \sum_{i=1}^{k} (f_i * w_i) \qquad (1)$$

$$w_i = \overline{X} = \frac{1}{n}(X_1 + X_2 + ... + X_n)$$

Where,

f = Factors contributing towards a good quality cost estimate (characteristics)
w_i = Corresponding weight of each (f_i) factor
X_n = The rating value of the n^{th} survey respondent, corresponding to each (f_i) factor (2^{nd} stage of survey results)

For every f_i and w_i, w_i stays constant while f_i varies depending on the level of satisfaction that this particular factor has met. Each factor corresponds to one of the 28 characteristics of a good quality cost estimate. The value of each f_i is the actual rating that a cost estimate reviewer would provide for that particular characteristic, with regards to a cost estimate. Additional details as to how exactly this method is applied are provided in Chapter 6.

Subsequently, the relative quality of a particular cost estimate could be represented with equation (2). The result of this equation could be represented as a percentage value, in order to provide interest parties with a common, comparable, scale.

$$Q_{toolindication} = \frac{Q_{rated} - Q_{\min}}{Q_{\max} - Q_{\min}} * 100(\%) \qquad (2)$$

Where, $Q_{\max}$ is occurring for all f_i being rated with the highest possible values and $Q_{\min}$ occurs for all f_i being rated with the lowest possible values, following a cost estimate review.

An assumption made in the definition of the proposed equation was that each factor does not contribute towards the attainment of the overall quality of a cost estimate, on an equal basis (see Assumption 1).

Assumption (1): $w_1 \neq w_2 \neq ... \neq w_k$

For example 'documentation of data sources' may be more important than 'identification and evaluation of potential risks'. Saying that, it could be the case that a couple of factors do actually contribute the same amount towards an estimate's quality (according to the survey participants' responses); however, for the whole of the count of factors there should be some variation to the extent of their contributory amount. In order to validate that this assumption stands true, survey participants were requested to provide their perceptions regarding each characteristic.

5.3.2 Follow-up Survey to Quantify Perceptions

As presented earlier, the purpose of the follow-up survey was two-fold: firstly, to validate the final list of the identified characteristics, and secondly, to quantify the importance of each characteristic towards an estimate's quality.

An assumption was made by the author that the relative influence of each characteristic towards an estimate's quality varies. That implies that not all characteristics are equally important towards an estimate's quality; and subsequently, some of them are going to be more important than others. The 'importance' is quantified in this study in terms of the relative weight that each characteristic has towards the overall estimate quality. This was derived based on the survey participants assigning rating values against each characteristic. The use of the semantic scales in the questionnaire (as described in Section 5.2.2) enabled the participants to express how important these characteristics feel that they are, towards an estimate's quality.

The analysis of the data collected during the second stage of the survey was quantitative in nature. Initial analysis of the data consisted of the use of descriptive statistics. Comparison of the average values (rated by the participants) of all the characteristics took place, in order to identify differences in terms of influence of each characteristic towards the overall quality of an estimate.

In addition, a commercial statistical software tool (SPSS) was used in order to find out whether there are any statistically significant differences between the various groups comprising the survey sample. Such comparison was carried out through the utilisation of the analysis of variance (ANOVA) technique.

5.3.3 Results of the Follow-up Survey Stage

The characteristics were ranked in terms of their overall mean value, based on the ratings of the survey respondents. Table 5.7 presents the results of the ranking exercise for the final list of 28 characteristics. A high mean value for a particular characteristic implies that the survey participants felt that this characteristic is very important, where a low mean value implies the opposite. It has to be noted that the values in Table 5.7 are rounded.

Table 5.7 – Ranking of the 28 Characteristics, based on their Mean Values

Rank	Characteristic	Mean	St Dev
1	Documentation of Rules and Assumptions made	6.6	.6
2	Including a clearly defined scope of work	6.4	.8
3	Estimate is delivered on time	6.4	.8
4	Accuracy (specific to the type of estimate/business need)	6.4	.5
5	Credibility and reliability of data & information sources (whether the sources are people or databases/documents)	6.1	.8
6	Simple and clear presentation of the results	6.1	.8
7	The choice of estimating method (and the effort spent) is appropriate for the final use of the estimate	6.1	.9
8	Awareness of the manufacturing quantity & production rate(s)	6.0	1.1
9	Estimate summarises main cost elements (breakdown into the various cost elements such as, labour, materials, sub-contractor involvement and so on)	6.0	.7
10	Estimate updated for economic period	5.9	.9
11	Documentation of data sources	5.9	1.1
12	Identification and evaluation of potential risks (risk analysis included with the estimate)	5.8	1.1
13	Identification of cost drivers (for cost reduction purposes)	5.7	1.0
14	Provision of supporting documentation/report (covering every aspect of the estimate)	5.7	1.0
15	Provision of a Basis of Estimate (BOE) with the estimate	5.6	1.1
16	Completeness of the WBS/PBS/CBS of the estimate (how well defined it is for the type of the estimate carried out)	5.6	1.3
17	Estimate, or part of it, can be checked against a known cost (for example, a past 'similar to' estimate)	5.4	1.3
18	Assumptions made have been validated by a subject matter expert	5.3	1.0
19	Estimated cost benchmarked against industry norms (e.g. carrying out a market study of similar products)	5.3	1.3
20	Have other areas of the business contribute to the estimate (e.g. inputs from Finance, Operations and so on)	5.3	1.1
21	Estimate based on valid quotes of purchased content	5.2	1.3
22	Use of additional cost estimating techniques for the purposes of cross-check; or even check the estimate's output against an existing calibrated/proven cost model	5.2	0.9
23	Supplier (or other interested parties) buys-in the process/model	5.1	1.4
24	Estimate is based on high level of technical detail	5.1	1.3
25	Estimate/model calibrated to company's processes/rates	5.0	1.5
26	Peer reviewed	4.9	1.3
27	Following a (pre)defined process to generate the estimate (such as dpt. procedures)	4.9	1.5
28	Shown within the estimate a relationship to schedule	4.7	1.6

The author also observed that the characteristics with the highest mean value (for example the first 10 in the ranking table), exhibit the lowest standard deviation compared to the bottom 20 characteristics in the Table. This observation could potentially mean that the respondents' perceptions did not vary a lot when considering the first 10 characteristics (in the ranking table); thus being in an agreement as to these particular characteristics' importance towards the overall estimate quality.

The 'Documentation of Rules and Assumptions made' attracted the highest score during the survey. Many respondents commented that having documentation to an estimate, and especially the all-required 'paper-trail', provides justification and adds credibility. As identified in the literature review, cost estimators do make assumptions during the generation of a cost estimate. Thus, it is important to provide visibility of their assumptions to others.

Ranked in second, third and fourth place were the characteristics of 'Including a clearly defined scope of work', 'Estimate is delivered on time' and 'Accuracy (specific to the type of estimate/business need)', respectively. Inclusion of the scope of work along with an estimate is crucial, since there has to be a clear scope that the cost and assumptions within the estimate are based on. The survey participants felt that it is quite important that a good cost estimate is delivered on time, to serve the required need.

The survey participants also felt that an accuracy level specific to the business need is an important attribute of a good quality cost estimate. However, this does not represent that estimate quality is related to its achieved accuracy, but rather that a good quality estimate must be 'accurate enough', depending on the type of estimate and business need. It is important to differentiate between these two different concepts in order to avoid drawing and misleading conclusions.

In addition, the survey participants felt that the credibility and reliability of the data sources, a simple & clear presentation of the results, the choice of estimating method, inclusion of economic conditions, the documentation of data sources and identification of potential risks, to name a few, are all important towards achieving a good quality cost estimate.

Risk results

At the end of the questionnaire, an additional question was included in order to identify if risk assessment should always be included with a cost estimate or not. The possible choices were 'Yes', 'No' and 'Depends on…', where a participant was asked to provide an explanation if the choice was the latter. The distribution of the answers is presented in Figure 5.4.

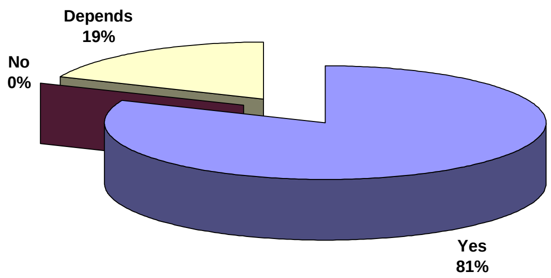


Figure 5.4 – Graphical Distribution Regarding the Importance of Risk

The majority of the sample, 81%, agreed that risk assessment should occur while carrying out a cost estimate; irrespectively. The remaining 19% of the sample stated that it depends on the circumstances whether a risk assessment should take place. A couple of those participants expressed that it depends on the intended business use of the estimate, as well as on the current product definition. One of the participants stated that estimates should normally be 'absolute', but there are occasions when high-risk uncontrollable economic conditions (such as exchange rates and material fluctuations) could be accounted for in the estimate in terms of risk. Finally, it should also be noted that the 'identification and evaluation of potential risks' has been ranked as 12th in the final list of the 28 characteristics.

5.3.4 Patterns Identified Amongst the Sub-Groups of the Sample

The next step in the analysis of the survey results was to compare the perceptions of the various sub-groups within the sample. This comparison could potentially reveal any underlying relationships between particular characteristics and sub-groups within the sample. Most importantly, it deemed necessary to explore whether the perceptions vary depending on the sub-group that survey participants belong to; thus validating or discarding the assumption that was made during the first stage of the survey: 'that the list of characteristics contributing towards a good quality cost estimate, are applicable to any industry, estimate purpose and cost estimating technique used' (assumption stated in Section 5.2.4).

The comparison was carried out by dividing participants into appropriate groups, and directly comparing their perceptions in the form of the mean arithmetic values. However, in order to be assured that any substantial differences are indeed statistically significant, the Analysis of Variance (ANOVA) tables were used to analyse the data. In the majority of the comparisons, there were two groups of responses which were compared at each given time; in which case the analysis provides similar results to carrying out Student's t-test for the various sample pairs. The complete results of the analysis are presented in Appendix D.1.2.

The various sub-groups were selected out of the sample based on a number of discriminators, such as 'Industry', 'Sector', 'Use of Cost Estimating Technique', 'Position' and 'Experience'.

Based on Industry

The comparison of the results, in terms of industry origin, was based on a split of the participants into two groups: Aerospace and the rest of industries represented. This was due to the fact that there were not many individual responses available to represent each industry group to a satisfactory degree. As a result, the sub-group

Table 5.8 – Top and Bottom 5 Characteristics for the Sub-groups based on Industry

		Characteristic	
	Rank	**Aerospace**	**Others**
Most Important	**1**	**Documentation of Rules and Assumptions made**	**Estimate is delivered on time**
	2	**Including a clearly defined scope of work**	**Accuracy (specific to the type of estimate/business need)**
	3	Simple & clear presentation of results	**Documentation of Rules and Assumptions made**
	4	**Estimate is delivered on time**	**Including a clearly defined scope of work**
	5	**Accuracy (specific to the type of estimate/business need)**	The choice of estimating method is appropriate to the final use of the estimate
Least Important	**25**	**Peer Reviewed**	**Peer Reviewed**
	26	**Following a pre-defined process to generate the estimate**	Use of additional cost estimating techniques for the purposes of cross-check
	27	Estimate is based on high level of technical detail	**Shown within the estimate a relationship to schedule**
	28	Other areas of the business contributed to the estimate	**Following a pre-defined process to generate the estimate**
	29	**Shown within the estimate a relationship to schedule**	Estimate calibrated to company's processes/rates

'Others' is a mix of participants from the automotive, energy, marine and consulting industries. Table 5.8 presents the five most and least important characteristics, as identified by the two sub-groups, ranked in terms of their mean value.

Figure 5.5 presents the comparison of the average mean values of each sub-group against each characteristic, along with a plot of the moving average. It should be noted that the characteristics' numerical identifiers are as per the results presented in Table 5.6.

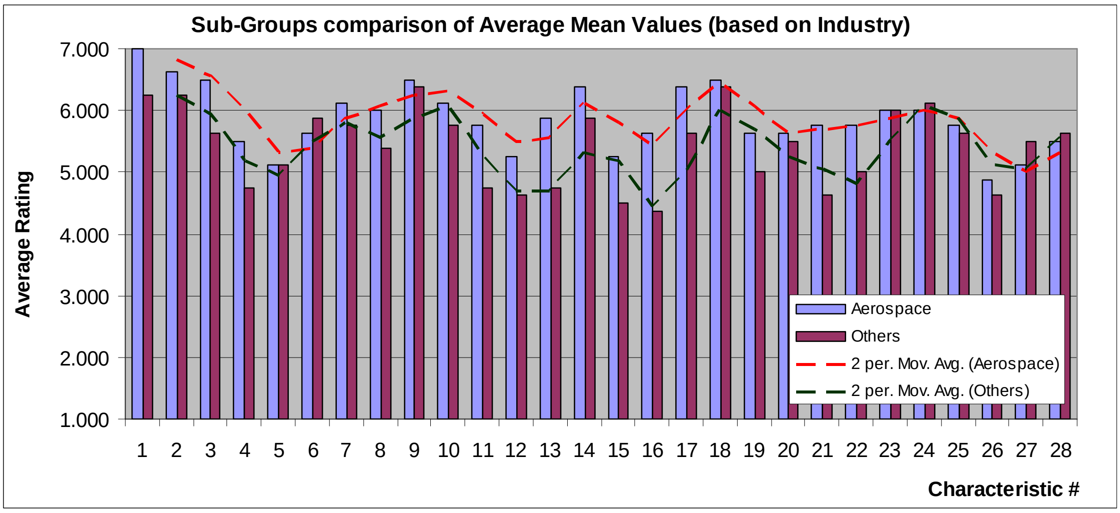


Figure 5.5 – Sub-Groups Comparison Based on Industry

Overall the two sub-groups exhibited a similar pattern in terms of perceptions. However, there are a few areas where perceptions differed between the sub-groups and the differences were determined to be statistically significant. Significant differences in perceptions were identified in the 'Documentation of Rules and Assumptions made' with the aerospace sub-group rating this characteristic much higher compared to the other sub-group. Differences were also identified in the perceptions regarding 'Simple and Clear presentation of the results' and 'Assumptions made have been validated by a Subject Matter Expert (SME)', again with the individuals belonging to the aerospace sub-group rating these two characteristics higher than their counterparts.

Finally, one of the strongest differences between the perceptions of the two sub-groups that were identified corresponded to the 'Use of additional Cost Estimating techniques for cross-check' characteristic.

Based on Sector

Two sectors were identified within the survey sample; the 'Civilian' and the 'Defence' sectors. Table 5.9 presents the five most and least important characteristics, as identified by the two sub-groups, ranked in terms of their mean value.

Table 5.9 – Top and Bottom 5 Characteristics for the Sub-groups based on Sector

		Characteristic	
	Rank	**Civilian**	**Defence**
Most Important	**1**	**Documentation of Rules and Assumptions made**	**Documentation of Rules and Assumptions made**
	2	**Including a clearly defined scope of work**	**Including a clearly defined scope of work**
	3	**Estimate is delivered on time**	**Estimate is delivered on time**
	4	Accuracy (specific to the type of estimate/business need)	Credibility & Reliability of data & information sources
	5	Simple & clear presentation of results	Awareness of the manufacturing quantity & productions rates
Least Important	**25**	Estimate, or part of it, can be checked against a known cost	Assumptions made have been validated by an SME
	26	**Shown within the estimate a relationship to schedule**	Use of additional cost estimating techniques for the purposes of cross-check
	27	Estimate calibrated to company's processes/rates	Other areas of the business contributed to the estimate
	28	Peer Reviewed	Estimate is based on high level of technical detail
	29	Following a pre-defined process to generate the estimate	**Shown within the estimate a relationship to schedule**

Figure 5.6 presents the comparison of the average mean values of each sub-group against each characteristic, along with a plot of the moving average.

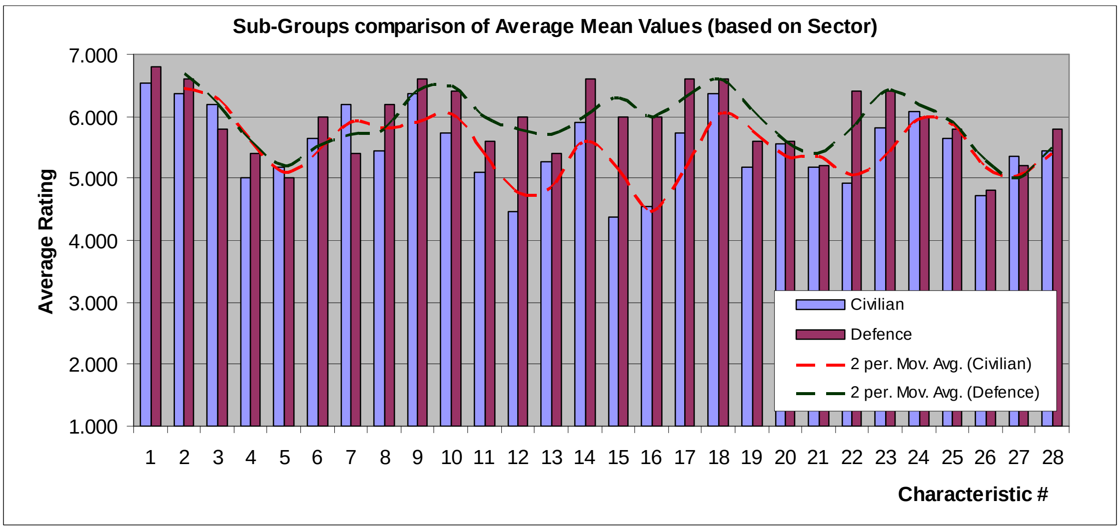


Figure 5.6 – Sub-Groups Comparison Based on Sector

Significant differences in perceptions were identified for the following characteristics: 'Peer Reviewed', 'Following a pre-defined process to generate estimate',

'Estimate/model calibrated to company's processes/rates' and 'Estimate, or part of it, can be checked against a known cost'. In all three cases, the Defence Sector had rated these three characteristics higher compared to the Civilian Sector. No other statistically significant differences were identified between the two sub-groups.

All four characteristics presented above are related to the review of estimates and procedures. The result does not come as a surprise since the Defence sector tends to be more procedure-driven than the Civilian sector, and employs more check-points throughout work processes; coupled with an increased amount of documentation.

Based on Cost Estimating Technique

The comparison of the results, in terms of cost estimating technique used, was based on a split of participants into two major groups: 'Detailed' and 'Parametric' techniques. Individuals were allocated to each group depending on which cost estimating technique they stated that they use the majority of their time to carry out cost estimates. Table 5.10 presents the five most and least important characteristics, as identified by the two sub-groups, ranked in terms of their mean value.

Table 5.10 – Top and Bottom 5 Characteristics for the Sub-groups based on Cost Estimating Technique

	Characteristic		
	Rank	**Detailed**	**Parametric**
Most Important	1	**Documentation of Rules and Assumptions made**	**Documentation of Rules and Assumptions made**
	2	**Estimate is delivered on time**	**Including a clearly defined scope of work**
	3	**Accuracy (specific to the type of estimate/business need)**	**Accuracy (specific to the type of estimate/business need)**
	4	**Including a clearly defined scope of work**	The choice of estimating method is appropriate to the final use of the estimate
	5	Estimate updated for economic period	**Estimate is delivered on time**
Least Important	25	Use of additional cost estimating techniques for the purposes of cross-check	**Shown within the estimate a relationship to schedule**
	26	Peer Reviewed	Completeness of the WBS/PBS of the estimate
	27	**Following a pre-defined process to generate the estimate**	**Following a pre-defined process to generate the estimate**
	28	Estimate calibrated to company's processes/rates	Other areas of the business contributed to the estimate
	29	**Shown within the estimate a relationship to schedule**	Estimate is based on high level of technical detail

Figure 5.7 presents the comparison of the average mean values of each sub-group against each characteristic, along with a plot of the moving average.

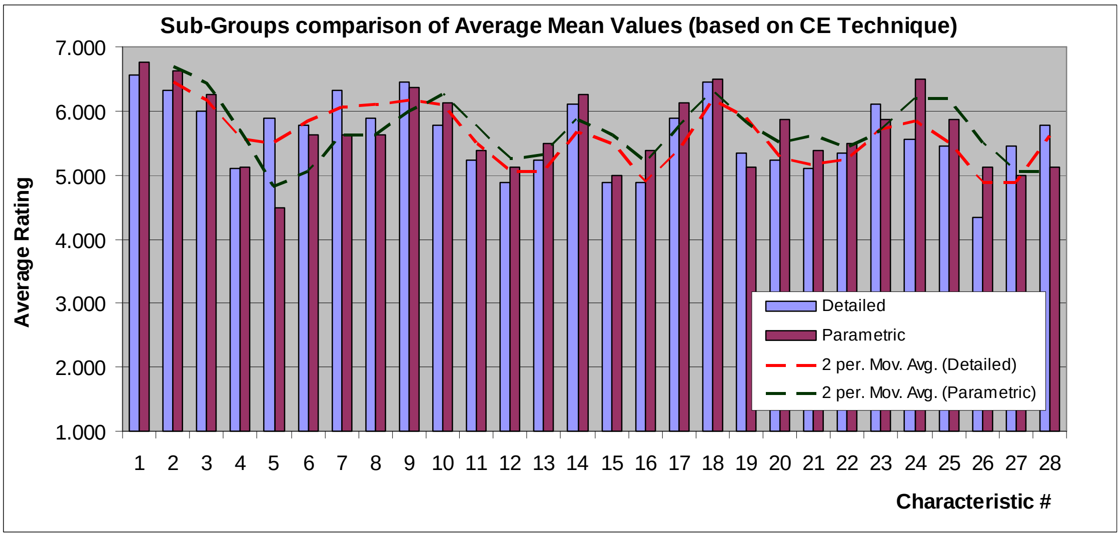


Figure 5.7 – Sub-Groups Comparison Based on CE Technique

Overall the pattern of the sub-groups perceptions is pretty similar, and does not exhibit any major differences. Significant differences in perceptions were identified for the following characteristics: 'Estimate is based on high level of technical detail' and 'The choice of estimating method is appropriate for the final use of the estimate'. Regarding the first difference identified, cost estimators who mostly use the detailed technique have rated higher this characteristic. In the second difference identified, cost estimators who mostly use the parametric techniques have provided higher ratings. No other statistically significant differences have been identified between the two sub-groups.

The difference in perception regarding the importance of the level of technical detail did not come as a surprise, since estimators who mostly carry out detailed estimates would naturally feel that the level of detail is quite important (when compared to estimators who carry out estimates based on a lower level of detail).

Based on Position

The next step was to investigate if there are any differences in perceptions depending on the position of the respondents. Thus, respondents have been split into two distinct sub-groups depending on whether they hold a managerial position or not. Table 5.11 presents the five most and least important characteristics, as identified by the two sub-groups, ranked in terms of their mean value.

Table 5.11 – Top and Bottom 5 Characteristics for the Sub-groups based on Position

	Characteristic		
	Rank	**Managers**	**Non-Managers**
Most Important	**1**	**Documentation of Rules and Assumptions made**	**Documentation of Rules and Assumptions made**
	2	**Including a clearly defined scope of work**	Estimate is delivered on time
	3	Completeness of the WBS/PBS of the estimate	Accuracy (specific to the type of estimate/business need)
	4	Estimate updated for economic period	**Including a clearly defined scope of work**
	5	Documentation of data sources	Estimate summarises main cost elements
Least Important	**25**	Estimate is benchmarked against industry norms	Use of additional cost estimating techniques for the purposes of cross-check
	26	Estimate summarises main cost elements	Estimate calibrated to company's processes/rates
	27	**Shown within the estimate a relationship to schedule**	Peer Reviewed
	28	Estimate is based on high level of technical detail	Following a pre-defined process to generate the estimate
	29	Supplier buys-in the process/model	**Shown within the estimate a relationship to schedule**

Figure 5.8 presents the comparison of the average mean values of each sub-group against each characteristic, along with a plot of the moving average.

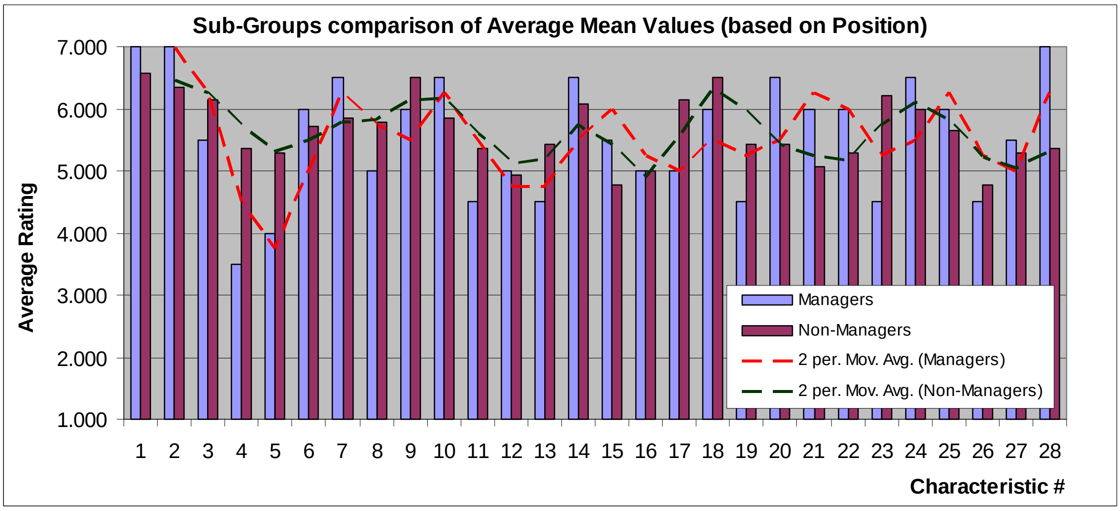


Figure 5.8 – Sub-Groups Comparison Based on Position

Overall the pattern of the sub-groups perceptions does not differ a lot. Significant differences in perceptions were identified for the following characteristics: 'Supplier buys-in the process/model' and 'Estimate summarises main cost elements', both rated lower by the 'managers' sub-group compared to their counterparts.

However, it has to be noted that the count of participants within the 'managers' sub-group was much lower compared to the count of participants in the 'non-managers' sub-group. Thus, there is a reservation as to the validity of this result due to the low count of responses within that sub-group.

Based on Experience

Finally, it was explored whether cost estimators of different experience levels have varying level of perceptions as well. The sample was split into three distinct sub-groups, based on the years of experience as cost estimators: '0-6 years', '6-11 years' and '11+ years'. Table 5.12 presents the five most and least important characteristics, as identified by the three sub-groups, ranked in terms of their mean value.

Table 5.12 – Top and Bottom 5 Characteristics for the Sub-groups based on Experience

		Characteristic		
	Rank	***0-6 Years***	***6-11 Years***	***11+ Years***
Most Important	**1**	**Documentation of Rules and Assumptions made**	**Documentation of Rules and Assumptions made**	**Documentation of Rules and Assumptions made**
	2	Estimate summarises main cost elements	**Accuracy (specific to the type of estimate/business need)**	**Estimate is delivered on time**
	3	The choice of estimating method is appropriate to the final use of the estimate	**Including a clearly defined scope of work**	**Including a clearly defined scope of work**
	4	**Including a clearly defined scope of work**	Estimate updated for economic period	**Accuracy (specific to the type of estimate/business need)**
	5	Awareness of the manufacturing Quantity & production rates	**Estimate is delivered on time**	Credibility & reliability of data and information sources
Least Important	**25**	Other areas of the business contributed to the estimate	Assumptions made have been validated by an SME	Estimate is based on similar-to products (use of actuals)
	26	Completeness of the WBS/PBS of the estimate	Awareness of the manufacturing Quantity & production rates	**Estimate calibrated to company's processes/rates**
	27	Peer Reviewed	Estimated cost benchmarked against industry norms	Estimate is based on a high level of technical detail
	28	**Estimate calibrated to company's processes/rates**	**Shown within the estimate a relationship to schedule**	**Following a pre-defined process to generate the estimate**
	29	**Following a pre-defined process to generate the estimate**	Supplier buys-in the process/model	**Shown within the estimate a relationship to schedule**

Figure 5.9 presents the comparison of the average mean values of each sub-group against each characteristic, along with a plot of the moving average.

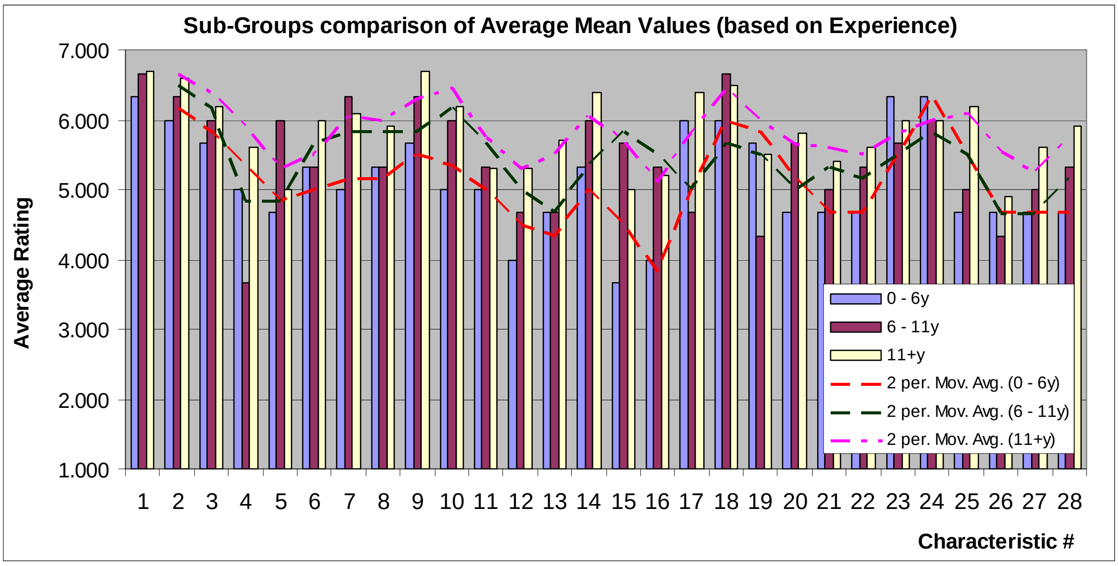


Figure 5.9 – Sub-Groups Comparison Based on Experience

The '0-6 years' sub-group's ratings pattern was slightly different compared to the other two sub-groups. The '6-11 years' and '11+ years' sub-groups did not exhibit any major differences between them. Significant differences in perceptions were identified for the following characteristics: 'Supplier buys-in the process/model', 'Accuracy (specific to the type of business need)' and 'Provision of supporting documentation/report'.

5.3.5 Final Observations

In summary, the comparison of the various sub-groups within the overall survey sample did not result in the identification of any major differences as to the perceptions of the cost estimators belonging to a particular sub-group. The results of the statistical analysis showed that there are not a lot of significant differences in perceptions. Based on these results, the author is led to believe that the perception of a good quality cost estimate does not vary much, irrespectively of industry, sector, cost estimating technique or position.

The respondents found the final list of characteristics to be representative, and they did not express any comments regarding any missing information. However, a couple of respondents commented that two of the characteristics in the list have very similar context; and it may be a good idea to merge them, since they believe they sort of repeating the same concept. The author wanted to find out if indeed that is the case, by analysing the data of the respondents' perceptions, which were elicited during the second stage of the survey. As a result, a correlation analysis was undertaken in order to examine whether there is any correlation between the data patterns of these two characteristics (and in fact if there is any strong correlation between any other pair of characteristics within the list). The analysis, which was carried out, is presented in Appendix D.2, presenting the resulting correlation matrix.

It was observed that these two characteristics have indeed a high degree of correlation between them (a correlation factor of .91). That implies that each individual respondent, part of the survey sample, has given an equal, or almost equal, weight to these two characteristics (either consciously or subconsciously). The outcome of the statistical analysis, confirms the suspicion that these two characteristics are similar in context, as expressed by a number of survey respondents as well, and thus they were eventually merged. As a result the 'Estimate is based on similar to products - use of actual/historical data' is merged to the 'Estimate, or part of it, can be checked against a known cost (for example, a past 'similar to' estimate)' characteristic.

The correlation analysis did not provide any other strong correlations between the remaining pairs of characteristics. Out of the total number of pairs, only three pairs exhibited correlation factors in the region of .8 to .85. Those pairs were analysed qualitatively, and it was pretty obvious that their context was not in any way similar and as a result they were discarded from any further analysis.

Thus, the final list of the inherent characteristics of a good quality estimate includes 28 characteristics in total, following the validation of the survey respondents. These characteristics could form the basis for assessing cost estimates, in terms of their quality. Further details as to how this was realised, are provided in Chapter 6.

5.4 Summary & Key Observations

In summary, in this Chapter the author presented the characteristics of a good quality cost estimate, which were identified following a survey across a sample of experienced cost practitioners. In addition, the respective weights of each characteristic were identified, based on the rating values provided by the survey respondents in a follow-up survey stage.

In Section 5.1, the author presented the rationale for carrying out a survey along with the survey design. In particular, the questionnaire design process was described, along with the sample selection and a number of other considerations regarding this survey type. The survey was carried out during two consecutive stages.

In Section 5.2, the first stage of the survey was presented, where a number of characteristics were identified, believed to contribute towards the quality of a cost estimate. A number of the results were shown to be consistent with the observations made during the literature review in Chapter 2, Section 2.3.2. The results were representative of cost estimates in general, as the sample make-up was generic in nature and did not focus on a particular experience level, cost estimating technique, sector and/or industry.

On the contrary to some of the findings in the literature review, only a handful of survey participants actually expressed that accuracy of an estimate could be considered as a measure of its quality. It was expressed that the concept of aiming towards a relative accuracy against a business need or estimate type is more important, rather than how accurate an estimate is against an actual cost. In addition, the nature of a number of the characteristics that were identified, led the author to believe that there must be a link between the knowledge used in developing a cost estimate and the quality of that cost estimate.

The review of the literature highlighted the lack of a quantitative, objective method to assess the quality of cost estimates. The implications of the findings suggest that indeed a method could be developed to assess quality based on the identified characteristics. In Section 5.3, the author proposed a novel method for assessing and quantifying the quality of a cost estimate based on the rating of the identified characteristics, and their relative importance towards the overall quality of a cost estimate. The relative importance of each characteristic was identified during the second stage of the survey. The survey participants were asked to validate the final list of characteristics and rate them based on how important they think each characteristic is towards the overall estimate quality. The results were analysed using a commercial statistical software tool. Amongst the various sub-groups some statistically significant differences were identified; however in overall, perceptions seem to be similar, not drastically varying due to a cost estimator's experience, industry, position, sector and/or cost estimating technique used.

The main findings of this Chapter could be summarised as:

- The identification of the inherent characteristics, which contribute towards the achievement of a good quality cost estimate. Essentially a deep understanding on what is the make-up of a good quality cost estimate.
- Cost estimators felt that there is a large amount of subjectivity currently involved in reviewing cost estimates; and any formalised method that could minimise this subjectivity would improve their current practices (further grounding some of the observations presented in Chapter 4).
- The relative importance (weight) of each characteristic towards the overall quality of a cost estimate was identified.
- As a result, the proposition of a novel method which could be employed in assessing and quantifying the quality of a cost estimate; thus, reducing the subjectivity that currently surrounds this process.
- The comparison of the answers of the various sub-groups within the sample did not exhibit any significant differences; leading the author to believe that the proposed method for assessing cost estimates quality could potentially be generic in nature.

In the following Chapter, the author presents the development of a tool which could be used to assess and quantify the quality of cost estimates. The tool is based on the proposed method, which was presented in this Chapter. The tool aims to increase the formalisation of the current CE processes, and form a basis for allowing novice cost estimators to develop better cost estimates, by identifying weaknesses in their estimate. This will essentially be integrated into the overall proposed framework within this study, with the aim of enabling novice cost estimators to develop cost estimates of improved quality.

CHAPTER 6 – DEVELOPING A TOOL FOR ASSESSING THE QUALITY OF COST ESTIMATES

In Chapter 5, the author presented the survey which was carried out with the purpose of identifying the inherent characteristics of a good quality cost estimate. Based on the results of the survey, a method was proposed which could be used to assess and quantify the quality of cost estimates. The aim of this Chapter is to test the proposed method, presented in Chapter 5, against actual cost estimates in order to examine its accuracy and effectiveness.

As a result, the Cost Estimate Quality Assessment (CEQA) tool was developed. There are two main reasons regarding the decision to develop a tool to test the proposed method: a) to have a means of interfacing with cost estimators in testing the proposed method, and, b) to be able to carry out the assessment of a cost estimate, and solve the equation, in a fast and automatic manner. Seven cost estimators used the tool for identifying how good their estimate is, resulting in 9 test-cases. The results of the proposed method were compared against the cost estimators' subjective judgement (perception regarding the quality of their estimates). Initial results suggest that the level of confidence predicted by the proposed method comes close to the subjective judgement of expert cost practitioners.

Finally, recommendations and validation results are presented from the sessions undertaken with each cost estimator who took part in the tool assessment.

6.1 An Instrument for Assessing the Quality of Cost Estimates

In this Section, the industrial need to develop a tool for assessing the quality of cost estimate is presented, along with the user requirements.

6.1.1 Developing a Means for Testing the Proposed Method

In Chapter 5, Section 5.3.1, equation (1) was proposed based on the results of the survey study. Additionally, it was identified that each characteristic has a different level of contribution towards the overall quality of a cost estimate. The proposition of equation (1) is based on the hypothesis that indeed the ratings (for each characteristic) provided by the sample of cost estimators during the survey, are representative of their perception of importance; and that the sum of the relative contribution of all of the 28 characteristics provides an indication of how good a cost estimate is.

In order to validate this hypothesis, the proposed method was benchmarked against actual cases; involving cost estimates which were developed by cost estimators, who were not part of the original survey sample. These individuals would be asked to provide a percentage value of how good a particular estimate, which they are familiar with, actually is. That value was based on their subjective perception of quality, developed through years of experience in the area of cost estimation. The author wanted to find out whether the equation predicts values close to the ones put forward by these individuals.

This approach provided a way of validating the hypothesis; that the characteristics identified, along with their respective weights, provide an indication of how good a cost estimate is. Particular attention was given in making sure that, firstly, the user testing the tool has not previously used it or been influenced by the outcome of the survey results, and, secondly that they state the indicated value (based on their perception) prior to using the tool. The author was present during the validation cases, to ensure that these conditions were met and that the user could ask any questions if required.

6.1.2 Further Considerations - Industrial Need

As presented in Chapter 5, a number of the participants expressed that a method, able to objectively quantify how good a cost estimate is, was required and would contribute towards increasing the credibility of their work. A method as such could be applied at the end of every estimating task in order to assess how good the quality of the output is, as well as for identifying areas of weaknesses within the cost estimate. Additionally, in Chapter 4, the author observed that currently organisations lack formal processes for assessing the quality of their cost estimates. In some organisations the estimate review process is unstructured and it only relies on an informal review of a cost estimate by peers. In other organisations, an estimate review process is lacking altogether, where there are no means to assess how good the resulting cost estimates are. Figure 6.1 illustrates how the method could be applied within a cost estimating environment, based on the TO-BE process presented in Chapter 4.

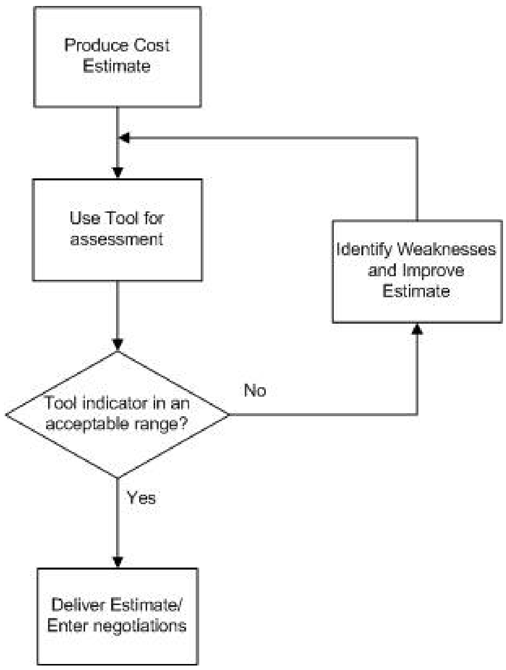


Figure 6.1 – Initial Estimate Review Using the CEQA Tool

Essentially the result from the proposed method could be used to identify the problematic areas of a cost estimate. Identifying areas of weaknesses as such, would guide a cost estimator in addressing the areas of potential improvement. This would be highly beneficial to novice cost estimators.

In addition, managers and any other decision-makers could benefit from such a method, as they would be equipped with a means to find out how good an estimate presented to them actually is. Quite often managers rely on the cost estimators to articulate to them how confident they think the result of their estimate is. Their decisions are based on, and influenced by, this crucial feedback between the estimators and themselves. A method which could objectively justify opinions as such, regarding the level of confidence, would aid decision-making and contribute towards the formalisation of the overall estimate review process.

6.2 CEQA Tool Development

One of the main objectives upon developing the tool was the provision of a friendly user-interface platform to engage experts into validating the tool's underlying concept. In addition, the tool should be very simple to use and compatible with any windows-based pc station. Thus, it was decided to develop the tool using Microsoft Excel, enhancing its functionality with the use of Macros.

6.2.1 Target Audience

Prior to the development of the tool it was important to define the intended target audience. In general, the future potential users of the CEQA tool will be cost estimators. Both novice and expert cost estimators could benefit from using the tool. For the purposes of this study the intended user(s) were cost practitioners, who are working within industry in a cost estimating, or closely related, job role. Having actual professional experience in the area of cost estimating, allows them to be able to differentiate between which estimate is good and which one is not. Their experience is crucial in the development of such a perception through time regarding the quality of cost estimates.

Therefore, the cost estimators had at least four years of cost estimating experience. Four out of the seven cost estimators were highly experienced, with more than 15 years of cost estimating experience. Their average experience in CE, for the total of the 7 cost estimators, was approximately 16 years. Additional details regarding the cost estimators' background are provided in Section 6.3.2, Figure 6.3.

6.2.2 Tool Development Requirements

A summary of the requirements is presented in this Section. The requirements were defined based on the author's experience and informal discussions with experienced cost estimators. The identification of the requirements took into account the intended audience, the purpose of the study and the various assumptions made by the author regarding the user(s) experience and expectations. Table 6.1 provides a summary of the requirements and the rationale behind the decision to meet these requirements.

Table 6.1 – Tool Development Requirements

Requirements	Rationale
Simple to use	Using the tool should not require any special training or skills. User-friendly interface(s) should make its use simple
Quick to use	The overall assessment of an estimate should not consume large resources, especially in terms of time
Provide a meaningful indicator	The user(s) should be able to use the tool's result in order to make decisions. A means should be provided where the tool's result should be put in some sort of meaningful perspective
Guidance Notes	The provision of a user manual, with explanations of how to use the tool; and especially some guidance with how to rate the various characteristics found within the tool

The development of the tool was based on the requirements, presented in Table 6.1. As a result, a user manual was developed with the aim of assisting users navigating through the tool's various screenshots, as well as providing explanations to the users as to what the available rating schemas represent. Most importantly the user manual included a number of descriptions against each characteristic within the tool, thus providing a clear explanation to users as to what is required with regards to rating each characteristic. A complete copy of the user manual is presented in Appendix E.

In the following Section, the author presents in more detail the development of the tool along with its functionalities.

6.2.3 Tool Functionality

There are only three main sheets with which the user interacts. The rest of the sheets, where the survey data are stored, are hidden so the user is not able to tamper with the values. Another reason was that the author did not want the users to introduce any bias into the rating process, due to being aware in advance of the relative importance of each characteristic towards the overall estimate quality. Figure 6.2 presents the sequence at which the user navigates through the various sheets of the tool.

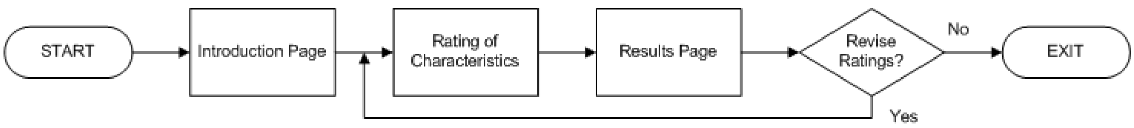


Figure 6.2 – Sequence of Functions within the Tool

Upon opening the tool, the first sheet that appears is the introduction page where the purpose of the tool is stated along with a set of instructions. Buttons are provided within each sheet in order to aid the navigation throughout the various pages; as well as for engaging the user into following the intended sequence (in using the tool). Figure 6.3 illustrates the introduction page.

Before moving on any further, the author would ask the cost estimator to state how good s/he believes the cost estimate under-consideration is, in terms of a percentage value. The author would typically engage in a conversation with the cost estimator at

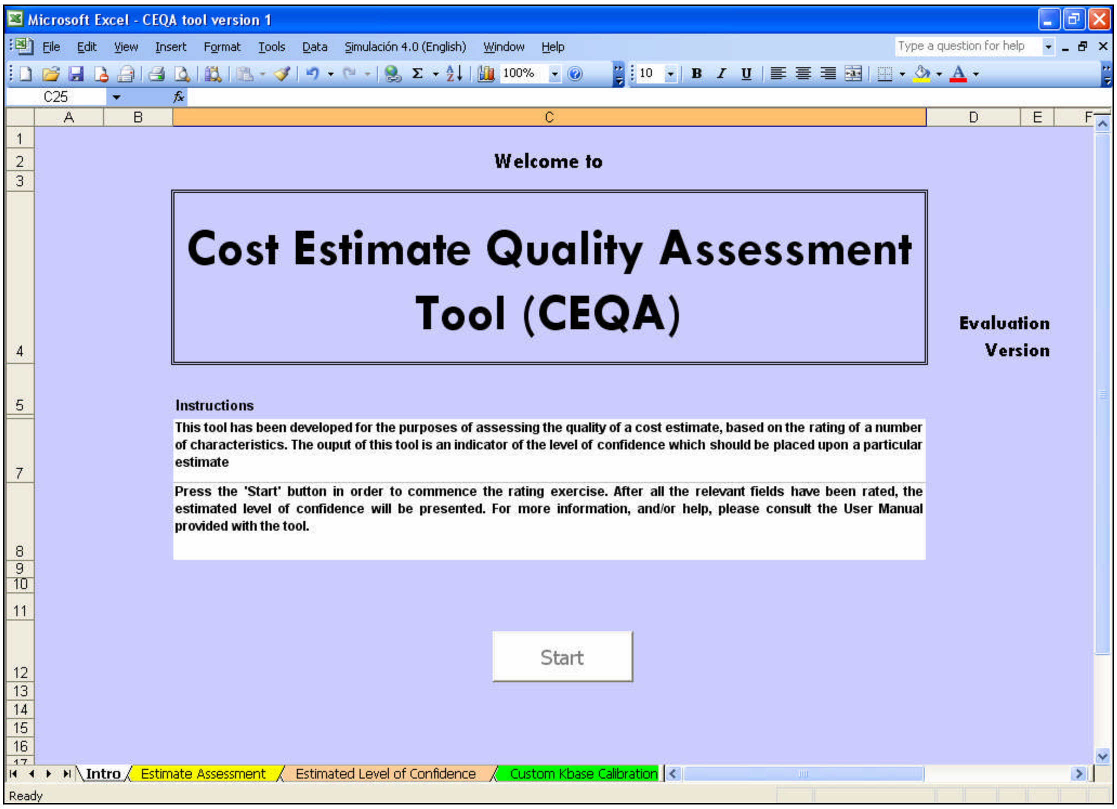


Figure 6.3 – Screenshot of the Introduction Sheet

this stage, in order to get a feel of what the estimate was about and how the user perceives that estimate in terms of quality.

Upon capturing this information the cost estimator would then be able to move to the next page and start the rating process. In this page the 28 characteristics are presented (in the form of questions). The cost estimator was asked to rate each one of them from 0 to 4 in terms of how good those characteristics were fulfilled based on that particular cost estimate that they had in mind. The characteristics, and thus the corresponding questions listed within the tool, were grouped under seven distinct categories based on similarities found with regards to their context. Table 6.2 presents the 28 characteristics of a good quality cost estimate, sorted into the seven categories.

Table 6.2 – The 7 Areas of an Estimate's Quality Assessment Process

	Category	Questions within Tool (Characteristics)
1	**Estimate Purpose & Conditions**	
	1.1	Was the estimate based on a clearly defined scope of work?
	1.2	Does the estimate appear to be updated for economic period?
	1.3	Are the manufacturing quantity and productions rate(s) included with the estimate?
2	**Estimate**	
	2.1	Are the results of the estimate presented in a simple and clear manner?
	2.2	Does it appear that the estimate is based in a high level of technical detail?
	2.3	Has a pre-defined process been followed in order to carry out the estimate (such as department procedures)?
	2.4	Has the estimate/model been calibrated to the company's processes/rates?
	2.5	Is there a Basis of Estimate (BOE) provided with the estimate?
	2.6	Does the estimate summarize the main cost elements involved (eg. Breakdown into labour, materials, sub-contractor involvement etc)?
	2.7	How complete/defined is the estimate's WBS/PBS/CBS for the type of estimate that is carried out for? (according to its purpose)
3	**Documentation**	
	3.1	Have the rules and assumptions made been documented?
	3.2	Have the data sources used been documented?
	3.3	Has a report/documentation been submitted with the estimate, covering every aspect of it?
4	**Data & Knowledge Utilised**	
	4.1	Has the estimate been based on valid quotes for purchased content?
	4.2	Are the data & the information sources used considered to be credible and reliable (whether the sources are experts or databases/documents)?
	4.3	Have other areas/departments of the business contributed to the estimate (such as inputs from Finance dpt, Operations etc)?
5	**Risk Identification**	
	5.1	Has an evaluation of potential risks taken place and the corresponding risks identified?
6	**Miscellaneous**	
	6.1	Have the cost drivers been identified (e.g. for cost reduction purposes)?
	6.2	Was the estimate delivered on time?
	6.3	Do you think the choice of cost estimating method and the effort spent on the estimate is appropriate to its final use?
	6.4	Is there a relationship to schedule, shown within the estimate?
7	**Estimate Validation**	
	7.1	Has the estimate been reviewed by peers?
	7.2	Has the supplier (or other interested parties) bought-in the process/model?
	7.3	Have the assumptions made been validated by a subject matter expert?
	7.4	Is the estimate accurate (specific to the type of estimate/business need)?
	7.5	Has the estimated cost been benchmarked against industry norms (like carrying out a market study of similar products)?
	7.6	Have any additional cost estimating techniques been employed to cross check; or has the estimate's output been checked against an existing calibrated/proven cost model?
	7.7	Is it possible to check the estimate, or part of it, against a known cost (for example, a past 'similar to' estimate)?

Figure 6.4 presents a screenshot of the estimate assessment sheet. The user would have to go through each question, corresponding to each of the 28 characteristics, and assign a rating value against the particular cost estimate that s/he had in mind.

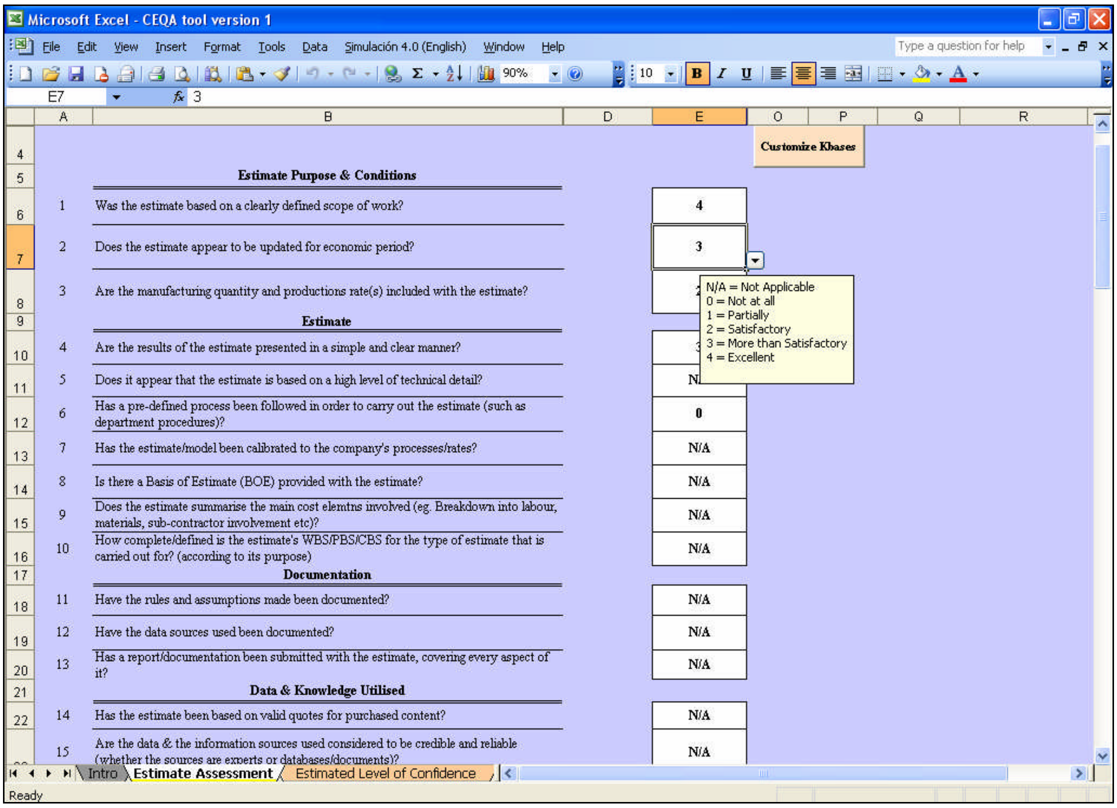


Figure 6.4 – Screenshot of the Estimate Assessment Sheet

A tag with a description of the possible rating options is displayed whenever the user is ready to rate a particular characteristic. Additional explanations regarding the available rating options are listed in the CEQA tool user manual. A cost estimator is also provided with the option of assigning a rating value as non-applicable (N/A). A N/A rating would result in the exclusion of this factor from the calculation of the perceived quality of a cost estimate (see equation 1, Section 5.3.1).

Finally, once the rating of all the characteristics was completed, the cost estimator would then be guided to the results page. The resulting indicator for the overall estimate quality is presented as a single percentage value. It was decided to present the result of the indicator as a percentage for two reasons: firstly people are familiar with the percentage scale (something they could relate to), and secondly, it would be easier during the validation process to think of an estimate's quality as a percentage (when they were asked to provide their perceptions). The resulting level of confidence, based on the rating of the 28 characteristics, is calculated based on the equation proposed in Chapter 5, Section 5.3.1. As described earlier, the tool's result is a level of confidence with regards to the adherence of quality into the cost estimating process, rather than a measure of the actual cost estimate numerical result. The characteristics' weights, presented earlier in Table 5.7, reside within the tool. The cost estimators did not have any visibility of those weights, throughout the duration of the exercise.

An example of the Results Sheet is presented in Figure 6.5, where the indicated value is presented to the user both as a percentage value and in a graphical way.

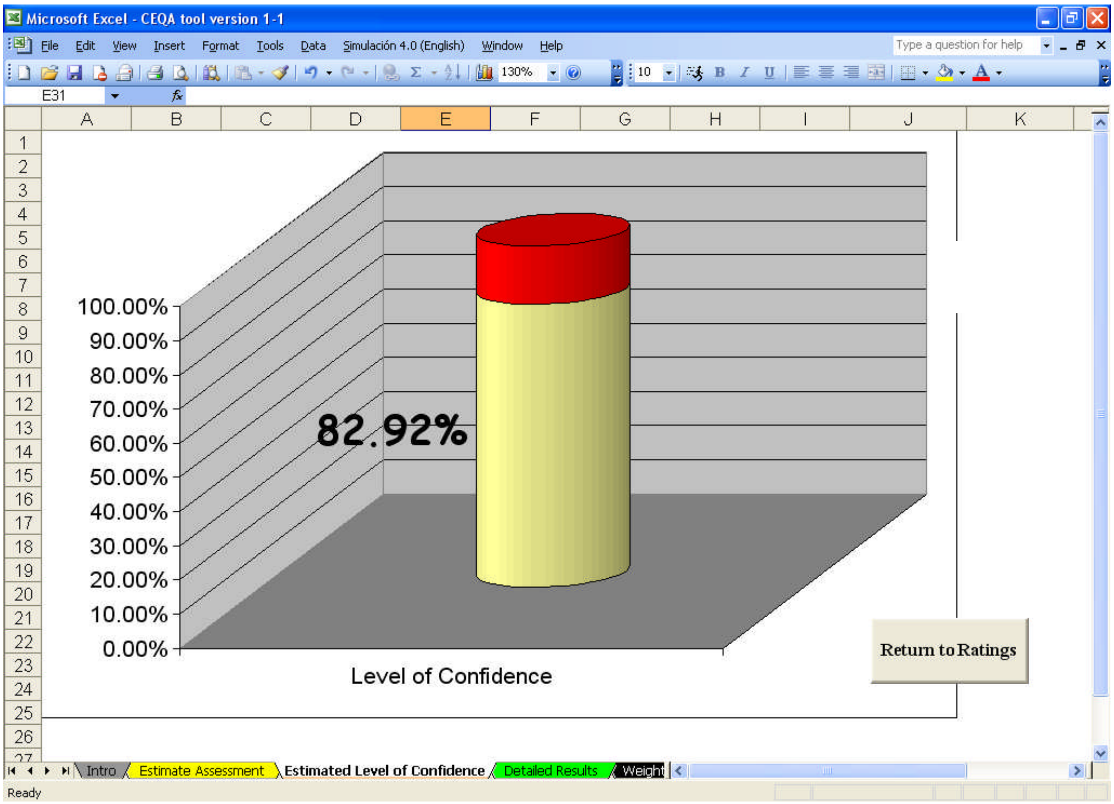


Figure 6.5 – Screenshot of the Main Results Sheet

When a cost estimator had rated all the characteristics and the result was displayed, the author would note down that value. The tool's result would then be compared against the user's perception which has been based on his expert judgement. A de-briefing session would follow amongst the author and the user, following the use of the tool. Finally, there is an additional results sheet where detailed results are presented, against each of the seven categories. The purpose of the breakdown of the overall result into the seven categories is to allow cost estimators to pinpoint quickly the potential areas of weaknesses within their estimates. A snapshot of the detailed results sheet is presented in Figure 6.6.

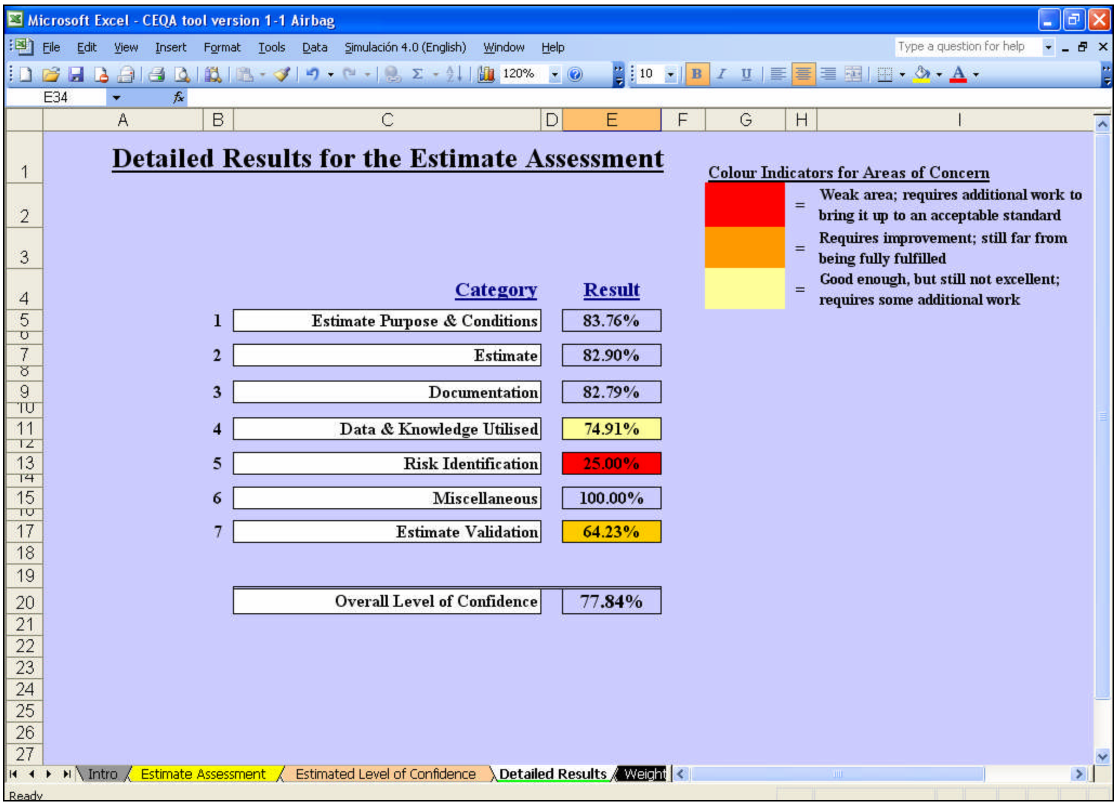


Figure 6.6 – Screenshot of the Detailed Results Sheet

In this Section, the development of the tool was presented. The following Section focuses on applying the tool on a number of test-cases, where actual cost estimates were assessed by cost estimators.

6.3 Validation of the CEQA Tool

In this Section, the results of the validation exercise are presented following the application of the tool in assessing estimate quality. In total, 9 test cases have been undertaken, three of which corresponded to using the tool during the case studies presented later on in this thesis. All the users who took part in this exercise were cost estimators with hands-on industrial experience; four of which had more than 16 years of cost estimating experience. They were asked to base the validation exercise on a past cost estimate of their choice; which could either include their own cost estimates or cost estimates of their peers that they may have reviewed in the past. The author monitored the process without interfering with the cost estimators, except when they needed some help regarding the use of, or the navigation within, the tool.

6.3.1 Introduction to the Test Cases

In this Section, the author presents a brief introduction to the test cases, on which the CEQA tool was tested against. These cases represent actual cost estimates, or estimating studies, for which the tool was used in assessing and quantifying their quality.

Network Study

A cost model was developed for estimating the cost of updating the existing nation-wide network of weather sensors and equipment, with one of increased capability. The cost model was used in decision-making, analysis of alternatives and the selection process of various installations.

Wing Rib Box

A cost estimate was developed for a wing rib box assembly of a civilian passenger aircraft, involving the use of new manufacturing technologies (in particular, the application of carbon composite structures in a wing structure).

Fan Cowl Door

A cost estimate was developed for a Fan Cowl Door, part of the nacelle of a civilian passenger aircraft. The purpose of the cost estimate was to identify the cost for manufacturing that assembly, in response to a customer's RFQ. Further details regarding the nature of the cost estimate are presented in Section 7.4.

Aircraft System

A cost model was developed for estimating the cost of the hydraulics system for a range of civilian passenger aircrafts. The purpose of the cost model was the estimation of costs of various system configurations, at the conceptual stage of the aircraft lifecycle.

Rib Assembly

A cost estimate was developed for a rib assembly, part of the wing of a military aircraft. The cost estimate was developed in response to a customer request for quote (RFQ). Further details regarding the nature of the cost estimate are presented in Section 8.1.

Airbag Cover Assembly

A cost estimate was developed for an airbag cover assembly of a sports car. The purpose of the cost estimate was to assess vendor quotes regarding that interior trim. Further details regarding the nature of the cost estimate are presented in Section 8.2.

Interior Door Panels

A cost estimate was developed for the interior panels of the doors of a sports car. The purpose of the estimate was to assess vendor quotes.

Radar Whole Life Cycle Analysis

A cost estimate was developed for a military helicopter radar system. The purpose of the estimate was to assess a supplier's financial offer against alternative solutions in the market, for the whole life of the programme. The cost estimate formed effectively a cost model which was used to undertake the selection.

Equipment Installation

A cost estimate was developed for the installation of a medium-size surveillance radar, on a military vessel. The purpose of the estimate was to assess a sub-contractor's quote, and form the basis for future negotiations.

In the following Section, the author presents the testing procedure, providing additional details as to how the tool was used in assessing the quality of these cost estimates.

6.3.2 Testing Procedure

Each cost estimator used the tool during a workshop facilitated by the author. Initially, a description of the tool and the workshop purpose was provided to the user along with a quick demonstration of the tool's functionalities. Once the cost estimators felt familiar with using the tool on their own, the author would ask them to think of a particular estimate that they recently carried out, or reviewed. The only exception to this was the test-cases regarding the three case studies, presented in Chapters 7 & 8, where the researcher was involved in the estimate assessment process that the cost estimators carried out. These are cases three, five and six respectively; as presented in Section 6.3.3, Table 6.4.

Initially, a short description of that estimate's purpose and characteristics were briefly discussed. The cost estimator would then be asked to state how good that estimate s/he thinks is, by providing a percentage value; where 100% represents a very good quality estimate and 0% an estimate of bad quality. No other instructions, or additional explanations, were provided to the cost estimator at this point.

The cost estimator would then use the tool and rate all the required fields, based on that particular estimate that s/he had in mind. Once the user would finish rating each characteristic, the final result would be recorded next to his earlier estimation (i.e. his subjective perception). A de-briefing session followed where the author interviewed the cost estimators regarding their experience with using the tool. A questionnaire was used to interview the cost estimators, a copy of which is presented in Section 6.3.5, Figure 6.8.

It has to be noted that the selection of the cost estimators was based on availability of contacts of the author at the time. The author aimed at collaborating with cost estimators who were not part of the original survey, in order to make sure that there was not any potential bias introduced to the results due to pre-conceptions, or expectations, which may have been formed during the survey study. Table 6.3 presents the background and experience of the cost estimators who took part in the tool validation. In total, seven cost estimators took part in testing the CEQA tool, over 9 test-cases.

Table 6.3 – CE Background & Experience of the Cost Estimators

Case	Estimator	CE Experience (in years)	Background
1	**User 1**	**5**	Background of cost estimating in the civilian sector, within the consulting industry. Largely dealing with cost studies & analysis. Mainly commercial background
2	**User 2**	**30**	Experience in the Civilian Sector, Aerospace industry. Background in engineering, cost estimating and commercial areas. Both strong technical & commercial background
3	**User 2**	*Same as above*	*Same as above*
4	**User 3**	**4**	Involvement in the civilian and defence sector. Mix of research & industrial experience. Both technical and commercial background
5	**User 4**	**27**	Experience both in the civilian and defence sector; part of an aerospace supplier. Both technical and commercial background. Senior managerial position
6	**User 5**	**26**	Experience mainly acquired within the automotive industry. Cost estimates, Should-cost, supplier quotes analysis.
7	**User 5**	*Same as above*	*Same as above*
8	**User 6**	**16**	A mix of civilian and defence background (MOD). Extensive experience in the systems integration industry. Involved in many aspects of CE
9	**User 7**	**8**	Experience in both civilian and defence projects. Involved in the manufacturing, aerospace and systems integration industries. Both technical and commercial background

In the following Section, the results of the 9 test-cases are presented, where the tool predictions are directly compared to the cost estimators' subjective perception.

6.3.3 Accuracy of Tool Predictions

The author recorded the results at the end of each session, and de-briefed the user regarding the exercise and the results. The de-briefing session included the use of a questionnaire, regarding the use of the tool and their overall thoughts on the subject. Table 6.4 presents a comparison of the results between the perceived values by the users, prior to using the tool, and the tool's results.

Table 6.4 – Summary of the Results of the Validation Exercise

Estimate Description	Expert's Perception	Tool Result	Actual Difference/Error	Deviation (%)
1. Network Study	80%	80.94%	0.94	1.18%
2. Wing Rib Box	90%	85.48%	- 4.52	5.02%
3. Fan Cowl Door*	85%	81.08%	- 3.92	4.61%
4. Aircraft System	55%	51.41%	- 3.59	6.53%
5. Rib Assembly*	90%	88.38%	- 1.62	1.80%
6. Airbag Cover Assembly*	85%	82.50%	-2.50	2.94%
7. Interior Door Panels	80%	56.68%	- 23.32	29.15%
8. Radar Solution Analysis	77.5%	73.94%	-3.56	4.59%
9. Equipment Installation	88%	85.23%	-2.77	3.15%
			Average Deviation	**6.55%**

The lowest deviation observed has a value of 1.18%, while the highest one has a value of 29.15% (estimate number 7). Overall the distribution of the results is skewed towards the lower observed deviation values. The average deviation between the tool and the experts' predictions, in terms of a percentage, was found to be 6.55%. In addition, the results indicate that in the majority of cases the perception of the cost estimators regarding their estimate is slightly higher than the tool's indicative result. Figure 6.7 graphically presents the tool's results against the cost estimators' perceptions. The diagonal line plotted on the graph corresponds to the line of 'no deviation', where a cost estimator's subjective perception is equal to the level of confidence calculated by the CEQA tool.

* These cases correspond to the three case studies carried out in this study. The application of the tool in these case studies is elaborated in Chapters 7 & 8.

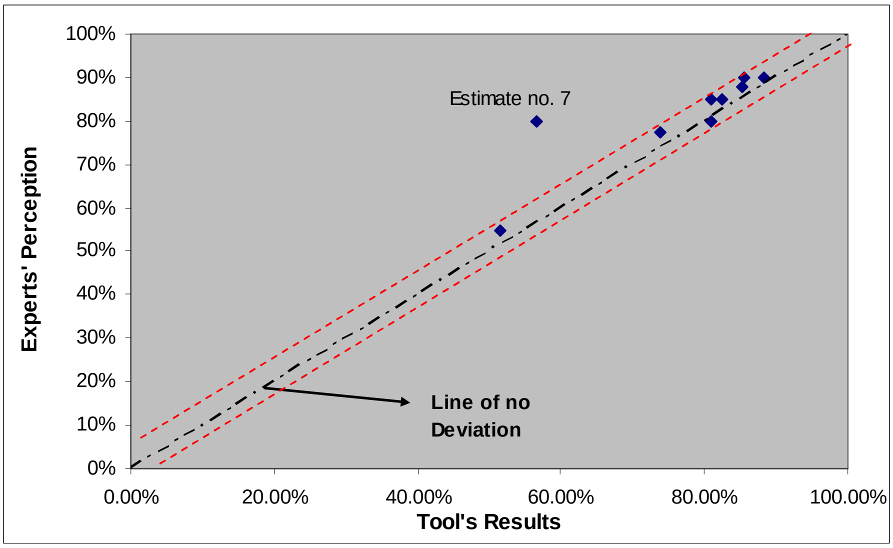


Figure 6.7 – Plot of Experts' Perception against Tool's Results; for the 9 Test-cases

It is clear from the plot in Figure 6.7 that the test-case number 7 exhibits the largest deviation compared to the rest of the test-cases. The author investigated that cost estimator's background, in order to identify any potential reasons as to why there was such a difference between the estimator's perception and the tool's result. That particular individual had around 26 years of experience. In addition, the majority of his experience was accumulated within the automotive industry. Thus, the author could discard that the potential deviation could be attributed to the estimator's non-familiarity with the subject (i.e. the content of the particular cost estimate, which he reviewed using the CEQA tool). The author was not able to identify any firm reasons as to why the test-case number 7 exhibited such a large deviation (29.15%), compared to the rest of the test-cases.

Another observation made during the validation exercise was that users tended to use rounded values in their subjective predictions (e.g. 80, 90, 75 and so on). It should also be noted that in the majority of the cases the perception of the cost estimators, regarding the quality of their estimate, was higher than the predicted value by the tool. The results seem to indicate that cost estimators believe their estimates to be slightly better than they actually are.

6.3.4 Results Interpretation

Finding out that a cost estimate is x% good in terms of quality means very little, since a percentage value could be interpreted in a different way by each individual, based on their personal experience(s). It was therefore necessary to attach some meaning to a group of the percentage ranges, with the aim of providing consistency in the interpretation and representation of the results. In order to put the results of the method in some meaningful perspective, a relationship of the tool's results against some form of descriptive terms needed to be provided.

The suggested interpretations of the five proposed ranges were based on comments provided by two experienced cost estimators during the validation exercise, with the use of the questionnaire presented in Section 6.3.5, Figure 6.8. The estimators were asked to provide their own interpretation of what the ranges within the 0 to 100% scale actually mean to them, in descriptive terms, as well as how they relate to the cost estimate development process. Table 6.5 provides the suggested interpretation of the possible range of values where the tool's prediction may fall into.

Table 6.5 – Suggested Interpretations of Tool's Indicator Results

Range	Interpretation
0 – 45%	Unreliable estimate. Areas of weaknesses in the CE development process should be identified and addressed
45- 65%	To be used for RoM purposes only and not as the basis of management decisions
65 – 80%	This level of estimate should used with written qualifications, stating assumptions where industry norms have been used in the absence of specific data
80 – 95%	Good level of satisfaction of the CE process. Estimate good enough to enter negotiations with, demonstrating a high level of confidence
95 -100%	Excellent fulfilment of the CE Process. An estimate on which to sign up contractually

The ranges proposed in Table 6.5 could be utilised in order to interpret the proposed method's results; and thus put in perspective the resulting values of the tool. Whenever the cost estimators were asked to provide their own interpretation of the ranges, they tended to relate their answers to decision making considerations and/or the quality of the CE process; rather than accuracy of the cost estimate itself. As described earlier within this Chapter, the tool's level of confidence is a measure of fulfilment of the characteristics of a good quality cost estimate. Thus, it directly relates to the adherence of quality in the CE development process. The findings with regards to the perceived quality of cost estimates, in Chapter 5, indicate that maintaining the quality in the CE process should result in a cost estimate of high perceived quality.

6.3.5 Qualitative Validation of Tool's Indicative Results

Upon completion of the testing session that took place with each cost estimator, the author asked a number of questions regarding the experience of the user(s) with the

Estimate Assessment Tool Validation

Name:

Results (please complete the table below based on the results from the tool):

	Your Estimate	Estimated Result by Tool
Estimate	XX.XX%	XX.XX%

1. After using the tool do you think any of the characteristics should not be taking part in the overall calculation of the estimated level of confidence of an estimate; and if so, why?

2. Is the tool simple to use?

3. Have you experienced any problems with using the tool? And have you found the user manual helpful?

4. After using the tool, do you believe that the estimated level of confidence is close enough to reality?

5. Finally, do you think this tool could be helpful into reviewing estimates at a very early stage; and do you believe it will help decision-makers trust an estimate more, if the estimate is supported by a tool as such?

Finally, I would like to relate the output of the tool to an easily understood expression. In your opinion, how would you categorise the result of the tool; more specifically, what the following ranges mean to you (in terms of how good an estimate is)?

Ranges	Description (Please express what the ranges mean to you)
0 – 45%	
45- 65%	
65 – 80%	
80 – 95%	
95-100%	

Figure 6.8 – Questionnaire used to Gauge User Experience with the Tool

CEQA tool. A questionnaire was used to gauge the experience of the estimators, and elicit their opinions regarding the suitability, fitness and correctness of the proposed method. In total, five completed questionnaires were acquired, out of the seven cost estimators. Figure 6.8 presents the questionnaire used by the author.

In summary, the cost estimators found the tool easy to use and were content that the tool does not require a lot of time for assessing the quality of a cost estimate. A number of estimators expressed their surprise of how close the tool's estimated value came to their own subjective perception. As a result, some users were intrigued as to how it works and required further explanations regarding the background equations that the tool is based on, in coming up with the level of confidence based on their ratings. Table 6.6 presents the results of the validation exercise that was carried out.

Table 6.6 – CEQA Tool Validation Results

Question	Reply 1	Reply 2	Reply 3	Reply 4	Reply 5
Is the tool simple to use?	Yes	Yes…definitely	Yes	Yes…(took me approx. 10min max)	Very simple
Have you experienced any problems with using the tool? And have you found the user manual helpful?	Yes, no problems at all	No problems with using the tool	No I have not. The user manual could include some additional examples of the available rating options though.	No I haven't	No
After using the tool, do you believe that the estimated level of confidence is close enough to reality?	It surprisingly is. I did not expect that to be honest	Yes…it is close enough	It certainly looks like it is	Think so.	I think so – I am confident with the tool confirming what I thought was the case
Finally, do you think this tool could be helpful into reviewing estimates at a very early stage; and do you believe it will help decision-makers trust an estimate more, if the estimate is supported by a tool as such?	We currently don't have anything like that in our company. I can see using this tool to track the progress of a cost estimate…definitely useful	Quite useful at corporate business management level. Finally, a tool is always good if you can add credibility to your work	The tool would have to be proven first, before it could be explicitly trusted. Following that, its application would definitely add credibility to the current process	Yes could be helpful; looking at the level of confidence you would expect to get in an estimate. In addition to the estimator's judgement, it could sit on top and provide to decision-makers some justification	Yes I could see the potential. I am particularly intrigued to see how we could implement this into our proposal reviews, so execs can have some independent view regarding how good a cost estimate is

In overall, all cost estimators agreed that there is value in implementing such a tool within their current processes, as a means of having an objective method of measuring up their estimating output. In addition, they did identify some value with regards to having a standard for comparing cost estimates; or even tracking their progress through the estimating lifecycle. One cost estimator commented that he could see the potential of using this tool to identify weaknesses in the organisation's cost estimating processes through the lessons learned that can be gained by establishing a formal estimate review process.

6.3.6 Development of the User Manual

It was apparent to the author that there will always be some kind of subjectivity involved in rating those characteristics using the scale provided, which cannot be completely eliminated. In order to minimise these subjective interpretations, the author developed some guidelines, which provide reference points as to what each value in the rating scale corresponds to. The guidelines were presented within the tool, in the form of a tag, each time a cost estimator would rate a particular characteristic.

In addition, there may be some bias involved in understanding the questions within the tool, as a result of misinterpreting what is being asked. The threat of such bias could however be minimised, and the author took the necessary precautions in addressing this issue, by providing detailed explanations as to what each question within the tool refers to. These explanations were listed in a user manual, where a potential user could consult if s/he is not sure what exactly is meant by a particular question. The full list of the supplementary explanations is presented in Appendix E, Section E.1, as part of the CEQA tool user manual. An example of such an explanation is provided below:

	Question	Explanation (if applicable)
18	Are the data & the information sources used considered to be credible and reliable (whether the sources are experts or databases/documents)?	Whether 'you' trust the data & information sources. How trustworthy are the people who provided you the inputs, or how credible do you believe the databases/documents you used are.

In the following Section, the author presents a summary of the results.

6.4 Summary & Key Observations

In this Chapter, the development of the CEQA tool was presented, which could be used to assess the quality of cost estimates. The tool was developed both as a means to interact with cost estimators in assessing the quality of cost estimates, as well as a way of validating the method proposed in Chapter 5.

In Section 6.1, the author presented the drive behind the decision for developing a tool for testing the proposed method, which was presented in Chapter 5. An explanation was provided regarding the potential contribution of such a method, and consequently the potential industrial need.

In Section 6.2, considerations regarding the target audience of the CEQA tool test-cases within this study were presented. In addition, the author identified a list of requirements concerning the tool development. Finally, the rationale behind the various required functionalities of the tool was presented.

In Section 6.3, the CEQA tool was applied by cost estimators in assessing the quality of actual, past cost estimates. The testing approach was presented along with the rationale in following this approach for testing the tool's effectiveness. The results from the test-cases were presented, where the tool's estimated values were found to be close to the estimators' subjective perception. As a result, the proposed method could be used to assess and quantify the quality of cost estimates. Following that, the author presented the qualitative validation of the tool's use, and results, where a questionnaire was utilised in gathering the users' experience with the tool. Finally, a discussion was provided as to the steps that were undertaken during this process in order to minimise any bias.

In summary, the key observations of this Chapter are summarised as:

- The proposed method for assessing the quality of a cost estimate was tested through the application of the tool on actual cost estimates, by a number of experienced cost practitioners. The method's results demonstrated a high correlation against the subjective judgement of these experts (regarding how good an estimate is); providing some confidence to both: a) the proposed equation to estimate quality, and b) the representativity of the elicited characteristics' weights.
- The cost estimators' perception seemed to be slightly higher than the tool's results. This could potentially indicate a degree of over-confidence regarding their work output.
- The diversity in the test-cases and the cost estimators' background, as well as the favourable results, lead to believe that the tool's effectiveness is not

constrained by industry, sector or estimating technique; thus, further confirming the observation presented in Chapter 5.

- It was identified that the implementation of this tool across the current practices could result in minimising the subjectivity which currently surrounds the estimate reviewing process.

In Chapter 5, the characteristics of a good quality cost estimate were identified, along with their relative importance towards the overall quality of a particular cost estimate. In this Chapter, the development of the CEQA tool was presented which could be used to quantitatively estimate how good the quality of a cost estimate is, based on the rating of these characteristics against a particular estimate. In the following Chapter, the development of a cost estimating knowledge elicitation methodology is presented. The CEQA tool could be used in conjunction with the methodology, as part of an overall framework, in providing cost estimators with a formal process which will help cost estimators with developing cost estimates of good quality.

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CHAPTER 7 – CE PROCESS IMPROVEMENT FRAMEWORK DEVELOPMENT

The review of the literature highlighted a lack of available methodologies, which novice cost estimators could use in order to elicit the required knowledge for developing a cost estimate. In addition, informal discussions with key practitioners from the collaborating organisations revealed that there are not methods as such applied in industry. There is a lack of pre-defined processes to follow for developing a cost estimate. Both the process and knowledge elicitation largely depend on the particular estimator and this skill is built on years of hands-on experience. These observations were confirmed by the results of the interviews with experienced cost estimators from industry, as presented in Chapter 4.

The lack of formalisation in the CE process was also identified within the results of the survey presented in Chapter 5. A number of the participants commented that they do not tend to follow pre-defined processes in developing a cost estimate, and that they believe formalisation would contribute positively towards developing better quality estimates.

In this Chapter, the author presents the development of the KC^2 methodology, which novice cost estimators could use in order to identify the 'key' knowledge required in carrying out a cost estimate. Initially, the essential methodology requirements in developing an effective and suitable KEL methodology are identified. Following that, the process of the methodology development is presented. The findings from Chapter 5, regarding the quality of cost estimates, are integrated with the developed methodology resulting into an overall framework. The purpose of the framework is to address the shortcomings identified in the current CE processes, and as a result improve the quality of the resulting cost estimates. Figure 7.1 graphically depicts the two distinct parts of the proposed framework. These parts were identified in the TO-BE process, presented in Figure 4.15.

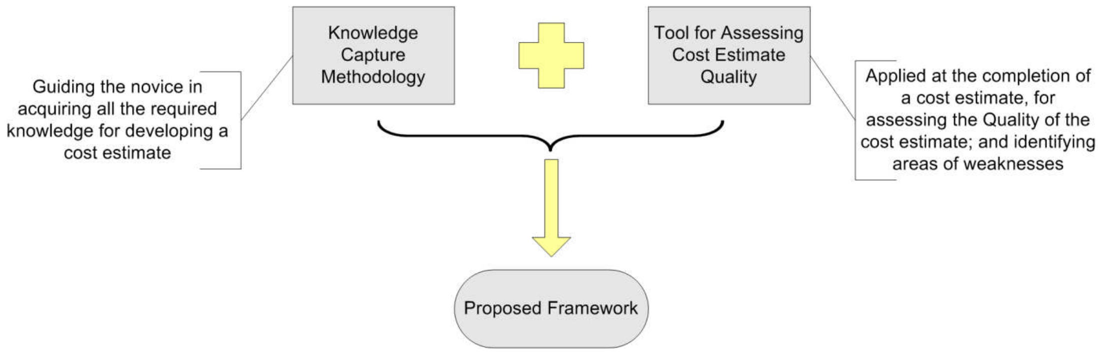


Figure 7.1 – Distinct Parts of the Proposed Framework

Finally, the framework was initially applied on a case study, in order to test its effectiveness and identify any potential weaknesses.

7.1 Defining the Requirements of the Proposed Framework

The development of the proposed framework was based on a number of criteria, identified to be crucial towards the attainment of a good quality cost estimate. In order for the framework to be effective and of value to novice cost estimators, the use of it should lead to the capture of data and information regarding the type of estimate, as well as the capture of key knowledge from the domain. The framework should also ensure that the method of carrying out a cost estimate is tailored to the characteristics identified in Chapter 5 as being paramount towards a good quality estimate.

7.1.1 Overall Requirements

A list of generic requirements was identified as being important to the development of the proposed methodology. The requirements were defined based on findings from the literature review and findings from the Chapters 4 and 5. In addition, during the identification and definition of these requirements, the end-user of this methodology was taken into account, as well as the views expressed by cost practitioners to the author during informal discussions.

The list of the identified criteria is presented in Table 7.1. The potential users of the proposed methodology are cost estimators; and in particular novice cost estimators. Based on the definition of what a novice cost estimator is considered as (presented in Section 4.2.4), a number of assumptions were made regarding the level of knowledge, understanding and expertise of the potential end-user(s) of the proposed methodology upon the definition of the requirements.

Table 7.1 – Requirements for the Development of the Proposed Framework

Criteria	Description
Simple to use	The techniques and methods, which will be part of the methodology, should be simple to understand and use by novice cost estimators, requiring minimal training/instruction.
Provide audit trail/ Documentation	By recording information sources, so a reviewer could trace back the origins of the knowledge utilised towards the preparation of a cost estimate; as well as any supporting documentation to an estimate. Documenting the process has been identified as highly important both in literature and in Chapter 5.
Record – re-use /Capture	Capture information in such a way that could be re-used again at a later stage; by re-visiting back the original documentation.
Structured – guide the process	According to Dreyfus (1986), a novice needs to adhere to strict rules in order to carry out a task; as the novice lacks the intuitive grasp of situations, and the application of judgement.
Novice learns - training aid	Assist the novice into understanding and associating key concepts within the domain; thus, making him less dependent on experts.
Transparency	Increase the transparency of the process of producing the cost estimate. It has been identified in Chapter 5, that transparency is key towards the achievement of a good quality cost estimate.
Generic approach	Can be applied for the cost estimation of hardware mechanical products of different kind(s).
Flexibility	The non-completion of some parts of the methodology should not hinder the completion of the whole process.

7.1.2 Requirements based on the CE Knowledge Needs

In addition to the overall generic requirements the methodology should incorporate the findings from the Chapters 4 and 5, in order to ensure that its use will result in developing a good quality estimate. In Chapter 4, the types of knowledge required by a cost estimator in order to produce a cost estimate were identified. A major consideration upon designing the proposed methodology was to enable the capture of these types of CE knowledge, when it is used for the purposes of developing a cost estimate.

This could be achieved by prompting novice cost estimators in eliciting all necessary data and information, which they may require for developing their cost estimate. The methodology should encourage the elicitation of data and information that were found to be related to the essential types of knowledge identified in the cost estimation of mechanical hardware products. A summary of the 10 types of knowledge identified in Chapter 4 is presented below:

1 Product/Functional
2 Design
3 Production
4 Manufacturing
5 Materials
6 Certification Requirements
7 Outsourcing

8 Contract/Project Conditions
9 Economic Considerations
10 Organisational

In Section 7.2, a detailed account of the considerations which were undertaken upon developing the proposed methodology is provided, and in particular how the various elements of the methodology contribute towards the capture of knowledge related to cost estimating. This was achieved by utilising a set of structured templates for capturing the required knowledge. The development of the templates was based on the types of CE knowledge identified in Chapter 4.

7.1.3 Integrating Quality in the CE Process

In Chapter 5, the inherent characteristics that are believed to lead to a good quality cost estimate were identified. The understanding about what contributes towards a good quality estimate led to the need of developing the proposed methodology in such a way that these characteristics would be fulfilled (to some degree), intrinsically by the use of the methodology. The intended users of the proposed methodology are cost estimators, and in particular novice estimators. Experts could also use the proposed methodology; however, it is the novices that are benefiting the most, since they lack experience and knowledge for developing cost estimates for products of a particular domain.

Embedding these characteristics into the methodology was believed to potentially allow novice cost estimators to produce good quality estimates first time; or estimates of better quality, than without it. Documentation, estimate transparency, provision of audit trail, following standard procedures (such as pre-defined process to carry out an estimate), estimate to be updated for economic period and peer review are some of the characteristics, which were identified during the survey as important towards achieving a good quality cost estimate.

The use of structured templates as part of the methodology would satisfy a number of the characteristics of a good quality cost estimate. It would provide the required documentation, and hence, the audit trail, as well as it would contribute towards increasing the transparency and credibility of an estimate. In addition, recording of all the data and information on which the cost estimator based his estimate upon, would make peer-review and validation of the estimate basis a straightforward task.

This would also contribute towards developing their personal knowledge in a much more structured and accelerated way.

Other considerations would be the provision of a way to record any assumptions made by the novice estimator. This would ease experts in the validation of those, as well as novices to have a complete and structured account of any assumptions they made under uncertainty of required inputs (and/or knowledge).

7.1.4 Providing a Means for Assessing the Quality of Cost Estimates

As part of the proposed framework, it would be beneficial to novice cost estimators to have a method, enabling them to assess the quality of their estimates. More importantly, to have an objective guidance in highlighting the areas of weaknesses in their estimates, so they can undertake any necessary actions for addressing them; and as a result, improving the quality of their estimate.

In Chapter 5, the author identified the inherent characteristics of a good quality cost estimate. Following that, in Chapter 6 a tool was developed utilising these findings, resulting in a method for assessing and quantifying the quality of cost estimates. The author suggested that this tool could complement the use of the proposed methodology, and become part of an overall framework. Following the use of the proposed methodology by the cost estimator in developing an estimate and eliciting all the required knowledge, the tool could be used to assess the quality of the estimate and identify any areas of weaknesses. The cost estimator could then address these areas and make improvements where possible. Following that, s/he could use the tool again to establish whether these improvements have resulted in a better quality cost estimate. This would be an iterative process, up to the point where the estimator and/or the estimate stakeholder(s), are satisfied with the resulting estimate quality.

7.2 KC^2 Methodology Development

The development of the KC^2 methodology was incremental and took place over two main stages. To begin with, the KEL methods reviewed in literature were analysed for suitability of eliciting the types of knowledge found in CE; as per the findings presented in Chapter 4. The requirements presented in Section 7.1, were used to 'shape' the proposed methodology. A conceptual structure was defined, based on the requirements enlisted in the previous Section, as well as the overall considerations.

7.2.1 Selection of KEL Methods

In Chapter 4, the types of knowledge were identified associated with the cost estimation of mechanical hardware products. Consequently, the nature of each type of knowledge was derived based on the available literature and the analysis of the results. In this Section, the types of knowledge are mapped against the available knowledge elicitation techniques (based on their pre-identified nature), in order to find out whether they are suitable and effective for eliciting these types of knowledge. A selection exercise took place where each KEL technique was weighted against the characteristics of the nature of the CE domain knowledge.

In addition to the identified characteristics, there are various practical issues that need to be considered in terms of knowledge elicitation. The time required to elicit the knowledge, the extent of access to subject matter experts and the training of a novice on a KEL technique, are examples of the important factors that need to be taken into account with regards to selecting suitable KEL techniques for eliciting cost estimating knowledge. The identification of these criteria was based both on suggestions from Klein *et al*. (1989), the author's understanding of the domain and informal discussions with domain experts. The purpose was to provide some practical considerations as to how suitable these techniques were for the proposed task; thus, three suitability criteria were identified: 1) time required to carry out the technique, 2) required access to expert(s) that a technique necessitates and 3) the training effort that an elicitor (in this instance a cost estimator) would require to expend.

Table 7.2 presents the selection exercise which was undertaken in order to identify which KEL techniques are suitable for which type(s) of cost estimating knowledge. Each technique was rated against the pre-defined criteria and an overall score for suitability was assigned; where a higher score means that the technique is most suited for the application. The scoring was influenced by knowledge regarding these KEL techniques, and the kind of knowledge they are intended to elicit. The basis of that influence originated from the literature review (with particular focus on Wellbank's (1987) categorisation of the KEL methods, presented in Table 2.4), as well as from the author's familiarisation with these techniques.

Table 7.2 – Matrix Table of Selection Criteria versus KEL Techniques (where 0/1=Not Suitable and 5=Extremely Suitable)

	Nature of Knowledge									Suitability Criteria			
KEL Techniques	Rules	Facts	Conceptual Structures	Procedural Knowledge	Casual Knowledge	Explanation	Justification	EJ	**Score**	Time Required	Access to Experts	Training/Familiarisation with technique	**Total Score**
Document Analysis	2	4	2	5	4	3	4	1	25	5	5	4	**39**
Semi-Structured Interviews	3	5	4	4	5	4	5	2	32	2	1	3	**38**
Card Sorting	3	2	5	1	1	3	3	2	20	2	2	3	**27**
Talk through Case Study	4	5	3	5	4	5	3	4	33	2	2	3	**40**
Composition Ladders	2	3	5	2	2	4	1	1	20	3	3	4	**30**
Repertory Grid analysis	4	2	5	1	1	2	1	1	17	2	2	2	**23**
Observation	2	4	2	4	1	4	2	2	21	2	1	4	**28**
Scales	1	2	5	1	1	1	3	1	15	5	3	4	**27**
Examining Prototype	4	4	3	2	1	2	2	1	19	3	5	5	**32**
Structured Templates	3	5	3	4	5	5	3	2	30	2	3	5	**40**

The scoring exercise presented in Table 7.2 highlighted the suitability of a number of KEL techniques for eliciting cost estimating knowledge. Methods with a particular high score, based on the suitability criteria, are the talk-through case study, the use of structured templates, semi-structured interviews, document analysis and examining prototype. The author feels that no single technique on its own can cater for carrying out the overall task; but a combination of the techniques under study would be more appropriate.

The talk-through case study method could be used during an interview or even during an informal discussion with an expert. In an effort of trying to understand how to carry out the estimate and what knowledge is required, the novice would initiate a conversation with the expert based on a similar past case. Questions would very much be of the 'why' and 'how' type, in order for the novice to gain an understanding of an expert's rationale.

Close examination of the subject, which the estimate is developed for, could provide a solid understanding of what is entailed, as well as any considerations regarding the various aspects of the product. Cost estimators should be encouraged to personally examine the product, or one of a similar nature, in order to better appreciate the production effort involved and any other potential costs incurred in the development of that product. During the interviews carried out with experienced cost estimators (presented in Chapter 4) many commented that their first step would be to have a close look at the product. This helps them to understand and visualise the activities involved in producing it.

The use of structured templates, although not explicitly a KEL method on its own, could be utilised to drive the KEL process. Designing the templates, tailored to the types of knowledge identified to be present in cost estimating, would enable a novice cost estimator to know what data and information to collect. The use of structured templates could be complimented by a list of generic questions, which should aid the estimator in asking the right questions to experts, while filling-in the provided fields.

Finally, another method that could be part of the proposed methodology is the composition laddering. The composition laddering technique did not score high compared to the rest during the selection exercise; however, it was found to be highly suitable for specifically eliciting hierarchical knowledge structures. Thus, it could be utilised for solely eliciting knowledge regarding the structure of a product, leading to the definition of a WBS/PBS. An additional advantage of using this technique is the resulting graphical representation of the knowledge elicited. This contributes both to understanding the product better, easing the validation process and also to representing the knowledge in an easily understood medium.

7.2.2 Methodology Conceptual Design

Based on the criteria defined for the development of the proposed methodology, a conceptual design was suggested. The main elements of the conceptual methodology are presented in Figure 7.2. The purpose of each one is further explained in the following Sections. The sequence of steps, presented within the boundaries of the dotted line, represent the natural behaviour of a typical novice. Novices would attempt to carry out the task on their own, and consult an expert only when facing any difficulties. This is the natural reaction of how a novice would behave in trying to carry out any kind of task; not just a cost estimate.

Bailey's (2003) KEN methodology is based on this notion, as presented earlier in the literature review. However, as discussed in Chapter 2, the KEN methodology is generic in nature and does not address the specific needs of the CE knowledge. Nevertheless, the author saw value in utilising this notion as the basis for developing the proposed KEL methodology within this study. The proposed methodology should address the shortcomings of the available KEL methodologies that were identified in the literature review.

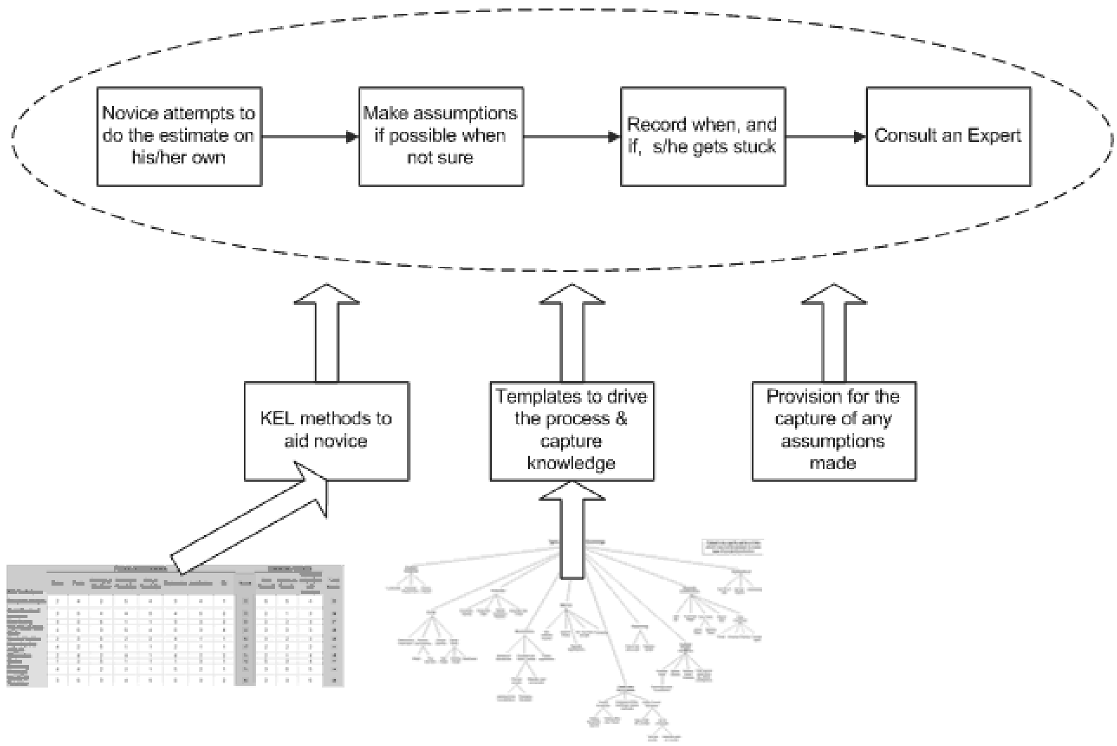


Figure 7.2 – Conceptual Structure for the Proposed Methodology

Starting with that basic notion, and considering the requirements presented in the previous Sections, the author proposed the incorporation of (as part of the proposed methodology) a selection of KEL methods, which were identified as being useful in aiding the novice in eliciting the required knowledge for completing his task. In addition, the findings from Chapter 4 regarding the types of CE knowledge and the typical data and information that an estimator would require for developing a cost estimate, were utilised. In overall, the methodology was structured in such way that all the objectives defined in the previous Section are addressed. Objectives as such include the generic requirements, the review of CE knowledge needs and the attributes of a good quality cost estimate.

All these pieces converged in forming the proposed methodology. A detailed account of the actual development of each individual part of the methodology is presented in Sections 7.2.3 and 7.2.4.

7.2.3 Generation of a WBS/PBS

When developing a cost estimate, typically a WBS (or a product breakdown structure for that matter) will be produced forming the basis of the estimate. Typical documents that could be used to derive a WBS are the customer's statement of work, or an available BOM. In that case the estimator would have to derive a breakdown structure based on any information available, as such. That breakdown could be presented to an expert at a later stage in order to check its fitness. The author observed that within the context of this study the developed structure reassembles more of a product breakdown, than a work one. A sound breakdown structure is a vital part of developing an estimate, as it forms the basis for any estimations carried out down the line (Stewart, 1995).

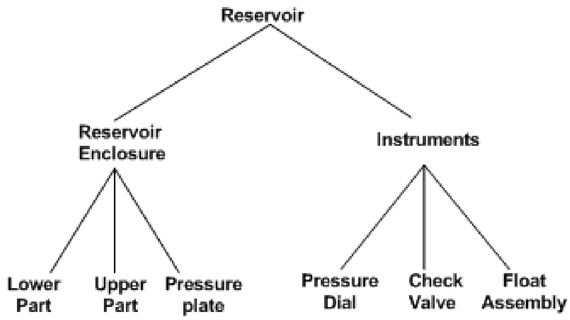
In the case where clear and/or useful information is not provided, or the novice is not able to comprehend it, the composition laddering technique could be applied to elicit the product breakdown structure from experts. As discussed earlier, the composition laddering technique is very effective at uncovering conceptual structures, and it also provides the additional advantage of graphically representing any knowledge elicited. The use of the composition laddering technique in conjunction with the use of probe questions is designed to make an expert contemplate and provide additional elements during the elicitation activity. A list of probe questions were developed to facilitate this process; presented in Table 7.3.

Table 7.3 – List of Probe Questions to be Used in Conjunction with the Composition Laddering Technique

	Probes
P1	Could the <*element of interest*> be further de-composed into lower hierarchical parts?
P2	Which are the main parts of the <*element of interest*> part?
P3	Do you agree with the current structure; or are there any changes you would suggest?

An example is provided to further describe the process, in Figure 7.3. In this example a novice cost estimator wanted to establish what parts and sub-systems an aircraft reservoir was de-composed into.

(a) Novice's current interpretation (b) Suggestions based on Expert's inputs



(c) Revised Structure

Figure 7.3 – An Example of the Steps in Applying the Composition Laddering Technique

The novice would present to the expert the 'current' understanding of the product's breakdown into the lower hierarchical components (Figure 7.3.a). The following conversation would then take place:

Novice: (P3) "Do you agree with the current structure; or are there any changes you would suggest?"

Expert: "Typically the pressure plate is an integral part of the case…and not an individual system on the same level. You could re-name the case as Reservoir enclosure…where all the parts, including the pressure plate, would be under it"

Novice: (P2) "Could the *Reservoir Enclosure* be further de-composed into lower hierarchical parts?"

Expert: "Yes, the *Reservoir Enclosure* for this type of aircraft typically consists of the *lower* and *upper case*, as well as a *pressure plate* which was mentioned earlier"

As a result, the novice could continue and revise the ladder based on the expert's feedback (see Figure 7.3.b). Then the novice would focus on each level 2 elements in a quest to find out the parts that they are de-composed into. The ladder evolves as a result of this iterative process (see Figure 7.3.c). The task is going to be completed when the expert cannot think of more sub-systems/parts, or when the novice is content with the level of detail that has been captured (specific to the purpose of the intended cost estimate).

7.2.4 Templates Development

Within the types of knowledge identified there is an amount of information required in order to produce a detailed bottom-up cost estimate. In Chapter 4, the modelling of the CE process, and eventually the identification of the individual cost elements, led to the realisation that a method was required, which would guide a novice in obtaining this information. The application of structured templates as a method to achieve this requirement was found to be the most effective and the most practical way (in terms of actual application within an industrial environment). The author analysed the knowledge requirements in order to identify the amount, and types, of templates that should be developed. Following the development of the knowledge tree in Section 4.3.3, the author attempted to categorise the various information elements into categories that share common attributes. Templates were developed for each identified class. The fields included in each template share some common theme and they are linked with logical relationships. This process was demonstrated at a high level.

Each mechanical hardware product may consist of a system/assembly, which in turn, is an accumulation of parts/components, or at least one stand-alone part. Consequently, each structural element (whether it is an assembly or a single part) is produced/assembled following a manufacturing process. Each manufacturing process consists of a number of individual manufacturing/assembly operations. The conceptualisation of relationships as such, is graphically presented in Figure 7.4 for a

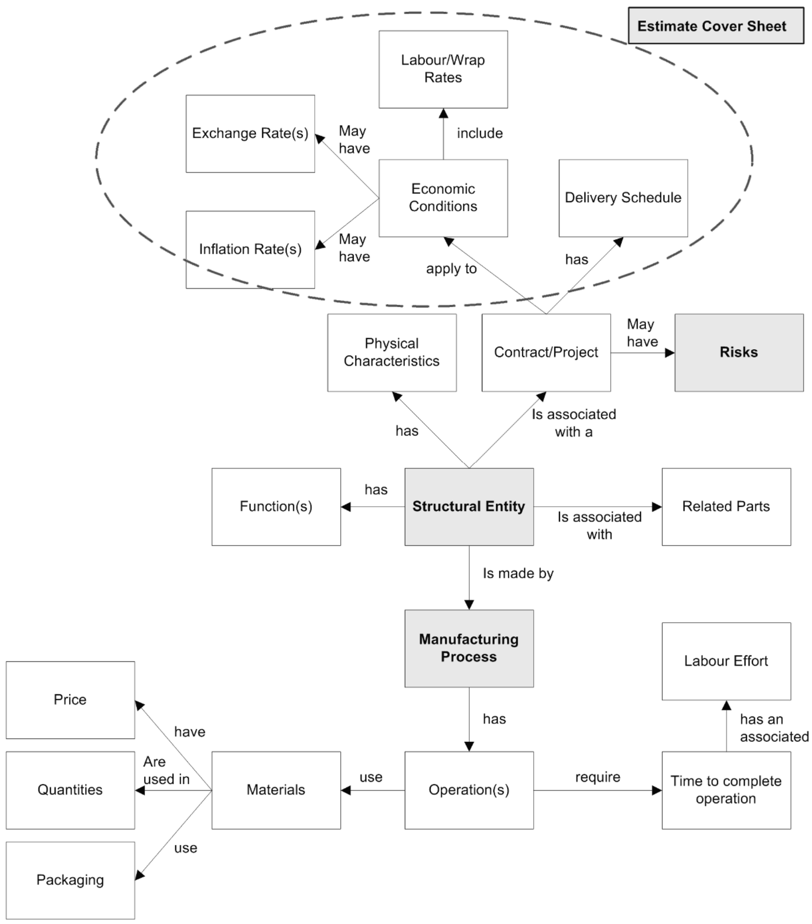


Figure 7.4 – Major Categories of the CE Knowledge

number of the main concepts. These concepts originated from the study of the types of CE knowledge, as presented in Figure 4.14.

At the end of the categorisation process, four distinct categories were identified: a) knowledge relating to a structural entity, b) knowledge related to the manufacturing process(es), c) knowledge related to the risks, and, d) knowledge related to the overall cost estimate considerations. In Figure 7.4, the shaded boxes represent the higher-level classes for which a template was developed. Most of the lower-hierarchical-order information fields, identified in Chapter 4, could be classified under those high level classes; forming the fields of those templates. The purpose of the diagrammatic structure presented in Figure 7.4 is to provide the reader with the author's rationale with regards to the development of the templates.

In the remaining part of this Section, the various templates developed, as part of the proposed methodology, are presented. The layout (visual format) of the templates for the proposed methodology was inspired by the ICARE templates of the MOKA methodology (Stokes, 2001). MOKA's ICARE templates, at their current state, were not suitable for satisfying the CE knowledge needs. As a result, the content of the fields in the proposed templates was based on the author's findings from Chapter 4. A couple of the non-domain specific fields, such as the field associated with the management of the template, were kept the same as within the ICARE templates.

Structural Entity Template

The structural entity template was developed in order to capture any information relating to a system or component, which is part of a product for which a cost estimate is developed. Some of the fields associated with this template are *function(s)*, *dimensions*, *method of manufacture* and *related parts/entities*. They were identified in Chapter 4. Figure 7.5 illustrates a structural entity template of the KC^2 methodology.

<table>
<tr><th colspan="4">Structural Entity</th></tr>
<tr><td>Name</td><td colspan="2"></td><td>P/N</td></tr>
<tr><td>Type (e.g. Ass., HW)</td><td></td><td>Hierarchical Level</td><td></td></tr>
<tr><td>Function(s)</td><td colspan="3"></td></tr>
<tr><td>Description</td><td colspan="3"></td></tr>
<tr><td>Dimensions/Drawing</td><td colspan="3"></td></tr>
<tr><td>In-house or Sub-contracted?</td><td colspan="3"></td></tr>
<tr><td rowspan="2">Method of Manufacture/ Assembly</td><td>Name</td><td colspan="2"></td></tr>
<tr><td>Description</td><td colspan="2"></td></tr>
<tr><td>Information Source</td><td colspan="3"></td></tr>
<tr><td rowspan="2">Related Parts</td><td>Parent</td><td colspan="2"></td></tr>
<tr><td>Child</td><td colspan="2"></td></tr>
<tr><td>Related Operations Characteristics</td><td colspan="3"></td></tr>
<tr><td rowspan="3">Management</td><td>Author</td><td colspan="2"></td></tr>
<tr><td>Date</td><td colspan="2"></td></tr>
<tr><td>Validation Status</td><td colspan="2"></td></tr>
</table>

Figure 7.5 – Structural Entity Template

Finally, a field for validating the information captured within the template is provided at the bottom of the template. In every kind of elicitation activity validation is of prime importance in making sure that the elicitor captured a concise understanding of the domain, as well as for providing traceability of the knowledge utilised during the cost estimate development. The structural entity template is also accompanied by a list of generic questions. The purpose of which is to help an estimator in asking the right questions, while attempting to fill-in the various fields of the template; thus, driving the elicitation activity. The generic questions are:

- Is the *Structural Entity* an Assembly or an individual Hardware Part?

- What is the Part Number of the *Structural Entity*?
- What is its hierarchical level in respect to the overall system/assembly?
- What is the function(s) of the *Structural Entity*?
- Could you provide a physical and functional description of the *Structural Entity*?
- Are there any engineering drawings available for this *Structural Entity*? If not, then could you approximate the dimensions of this *Structural Entity*, in order to get a feel of its size?
- Is the *Structural Entity* manufactured in-house, or is it out-sourced?
- What is the method of manufacture for the *Structural Entity*?
    - Could you describe the process in a bit more detail?
    - Are there any other related manufacturing operations, in addition to the main method of manufacture?
- Are there any related parts to the *Structural Entity*?
    - If so, then what are the lower hierarchical parts that the *Structural Entity* consists of?
    - Is the *Structural Entity* part of a higher-level assembly? If so, which one?

Manufacturing Process Template

The 'Manufacturing Process' template was developed for capturing any information with regards to the manufacturing operations undertaken, when producing a part/entity. Some of the fields associated with this template are *tooling requirements*, *manufacturing operations* (along with any estimating standards available and wrap rates), *materials used* and *related processes*. Figure 7.6 illustrates a 'Manufacturing Process' template of the KC^2 methodology.

<table>
<tr><th colspan="5">Manufacturing Process</th></tr>
<tr><td>Name</td><td colspan="4"></td></tr>
<tr><td>Manufacturing Process Description</td><td colspan="4"></td></tr>
<tr><td rowspan="2">Tooling Requirements</td><td>Tool(s) Life</td><td colspan="3"></td></tr>
<tr><td>Tool(s) Price</td><td colspan="3"></td></tr>
<tr><td rowspan="2">Manufacturing Operations</td><td>Name</td><td>Estimating Standard</td><td>Material Used</td><td>Wrap rates</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Materials Used</td><td colspan="2">Material Name</td><td colspan="2">Material Price</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Information Source</td><td colspan="4"></td></tr>
<tr><td rowspan="2">Related Processes</td><td>Parent</td><td colspan="3"></td></tr>
<tr><td>Child</td><td colspan="3"></td></tr>
<tr><td rowspan="3">Management</td><td>Author</td><td colspan="3"></td></tr>
<tr><td>Date</td><td colspan="3"></td></tr>
<tr><td>Validation Status</td><td colspan="3"></td></tr>
</table>

Figure 7.6 – Manufacturing Process template

Similarly to the Structural Entity template, a field for validating the information captured within the template is provided at the bottom of the template. The generic questions specific to the manufacturing process template, are:

- Could you provide a short description of the main manufacturing process undertaken in the production of this *Structural Entity*?
- In order to carry out the *Manufacturing Process*, are there any tools required? If so, then:
  - Could you provide a short description regarding the tool? What is its purpose?
  - What is the tool's life?
  - What is the tool's price (considering it will be out-sourced to a supplier)?

- What are the various manufacturing operations that the *Manufacturing Process* consists of?
- For each manufacturing operation:
  - What material(s) is required; and at what quantities?
  - Which labour (wrap) rate is applicable?
  - What is the time taken to complete this particular operation? Are there any estimating standards (and/or rule of thumb) that could be used to estimate the time?
- For the materials identified, what are the material prices? If not available, then what are typical market prices for such materials?
- Are there any related (and/or additional) manufacturing processes to the *Manufacturing Process*?

Initial Estimate Conditions Sheet

As identified in Chapter 4, there is a plethora of information associated with the development of a cost estimate, which may not be directly related to the product produced. Information such as project/contract conditions, economic considerations and labour rates are a few examples. Thus, a need was identified for capturing knowledge as such, which would influence the development of a cost estimate, in an explicit way, while following the same format to the two templates presented earlier. As a result, the author developed the Estimate Cover Sheet that could be applied for capturing high level cost estimate considerations. A copy of this template is presented in Figure 7.7.

Estimate Cover Sheet							
Estimate/RFQ							
Estimate Request Description (Scope)							
Production/Schedule Details	Production Quantity						
	Production Rate/Schedule						
Wrap/Labour Rates	Year	20..	20..	20..	20..	20..	20..
	Types of Wrap/ Labour Rates						
Economic Conditions	Inflation						
	Currency rates ... to ... (If Applicable)						
	Other Conditions, Mark ups and additional costs						
Other Estimate Considerations							
Information Source							
Management	Author						
	Date						
	Validation Status						

Figure 7.7 – Estimate Cover Sheet

The Estimate Cover Sheet should be used for recording any kind of high level considerations regarding the project or the cost estimate itself. Any economic and overall project considerations which may impact on a cost estimate, would also be captured in this template. The generic questions developed to accompany the Estimate Cover Sheet, are:

- Could you describe the purpose and scope of the intended cost estimate?
- What are the production quantity and the expected deliveries to the customer?
  - Is there a schedule available?
  - If so, could you highlight the major milestones?
- What types of wrap/labour rates are applicable to this kind of job?
  - List the different types (such as production, assembly and so on)
  - What are the rates for these categories? (provided in an appropriate format, such as $/hr, or $/min)
  - What is the expected escalation applied for those rates for the duration of the project/production? – (considering it lasts more than the current year)
- What are the economic conditions to be applicable to this estimate?

    - What escalation rates are applied (if applicable)?
    - If there is any currency content (either in the materials/sub-contractor element, or prices quoted in a different currency to the customer), what is the assumed exchange rate?
    - If there are any materials/sub-contractor prices, at what economic conditions are they quoted on?
    - Are there any additional mark-up costs applied to get to the true *Factory Cost*?
- Any other considerations which need to be taken into account?
    - Any other costs to be incurred, specific to this kind of job?

Assumptions Sheet

A cost estimator tends to resort into making assumptions while developing an estimate, due to the presence of uncertainty surrounding many of the inputs. The amount of assumptions made depends on various issues, such as current product definition, known project/contract conditions, the level of detail of the cost estimate and so on. These assumptions are often not captured and there is a lack of transparency regarding their application. This becomes apparent only when a third party attempts to review a cost estimate. Some of the respondents of the survey commented that transparency is often lacking, thus making it extremely difficult to check the validity of the inputs, and the associated assumptions, of an estimate.

It was decided that it is important to have a sheet solely developed for capturing assumptions associated with a cost estimate. On the contrary to experts, novices would often be unable to make an assumption when they would run into a difficulty. Thus, a sheet is provided to the novice for recording the points where the difficulty was encountered; in order to seek advice from an expert at a later stage. At that point the novice cost estimator may make an assumption, irrespectively of how invalid it may be, in order to be able to progress with the cost estimate. Such assumptions could also be captured in the sheet in order to be checked for correctness by an expert at a later stage. The development of the assumptions sheet was based on the notion presented in Figure 7.2. An example of the assumption sheet is presented in Figure 7.8.

Assumptions Sheet

This sheet should be used by the estimator, while carrying out the cost estimate, in order to record any assumptions made. This will help keep track of where the estimator gets stuck, and also this document will serve as a record to any of the assumptions present in the cost estimate.

Name:	
Estimate/Model:	
Date:	

Ass. #	Points where Novice got Stuck	Assumption Made	Question generated (if Applicable)	Expert's Response
1				
2				
3				
4				
5				

Figure 7.8 – An example of the Assumption Sheet

Upon the completion of the cost estimate, all the assumptions made would be presented to an expert for validation. The use of such approach provides the capture of those assumptions and a means to check their validity. In addition, it provides a medium to capture any cost estimating knowledge that experts provide to the novice cost estimator.

Risk Sheet

In Chapter 5, it was identified that one of the characteristics contributing to a good cost estimate was the identification of potential risks. The majority of the cost estimators who took part in the survey commented that identifying and addressing the potential risks of a particular project was highly important. Within an organisation risk management and analysis could be the responsibility of a separate. However, cost estimators are involved in this process, working along with risk practitioners. Thus, this is not an integral part of the cost estimating process, but rather something supplementary. Nevertheless, the author believes that the novice estimator should at least identify some of the risks which may have an impact to the final cost of the product. The analysis and management of such risks are beyond the scope of this study.

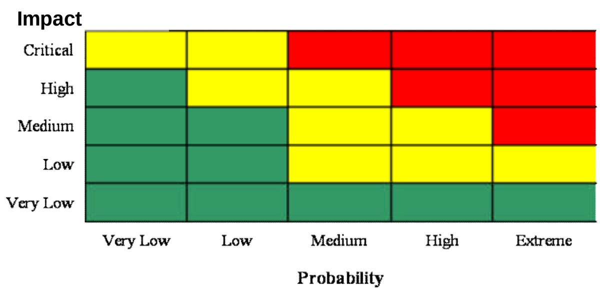
As shown in Chapter 4, knowledge regarding the risks to a project falls under the Contract/Project conditions knowledge category. The fundamental steps that should be captured by the novice are: a) what are the potential risks, b) what is the probability of occurrence and c) what would be their impact to cost if they occur. The risk sheet is presented in Figure 7.9. It would be completed by the novice cost estimator during the development of a cost estimate.

Risk Sheet

Name:	
Estimate/Model:	
Date:	

#	Risks	Description	Probability	Impact
1				
2				

Example used to assess the probability of a particular risk, and the potential impact to the project/product's cost.



Comments – Action(s) to be taken

Figure 7.9 – Risk Sheet

A list of generic questions is provided to accompany the Risk Sheet. The generic questions are:

- Are there any risks associated with the production of this product?
  - Technical risks (production capacity & rates, technical problems)

    - Technological
    - Economical
    - External risks (supply chain/sub-contractors)
- If so, what is the impact on cost that this risk would have if it materialised?
- What is the probability of this risk materialising?

In the following Section, the author presents the resulting framework.

7.3 Resulting Framework

In the previous Section, the development process of the proposed methodology was presented. In Section 7.3.1, the author brings together all the ingredients of the development process, resulting into a complete KEL methodology which could be used by novice cost estimators for eliciting cost estimating knowledge. In with Section 7.3.2, the additional elements are incorporated to the resulting methodology (elements such as the estimate assessment tool), in order to come up a complete framework, which could aid cost estimators in developing good quality estimates. Finally in Section 7.3.3, the author presents the approach undertaken in applying the framework into an industrial case study.

7.3.1 A Methodology for Eliciting Cost Estimating Knowledge

In Section 7.2, the development of the KEL methodology was presented along with its various elements. These included the selection of suitable KEL techniques based on the identified nature of cost estimating knowledge, the conceptual structure on which the *Knowledge Capture for Cost* (KC^2) methodology was based on, and finally, the development of the various templates and sheets. The incorporation of all these elements into a complete methodology is presented in Figure 7.10.

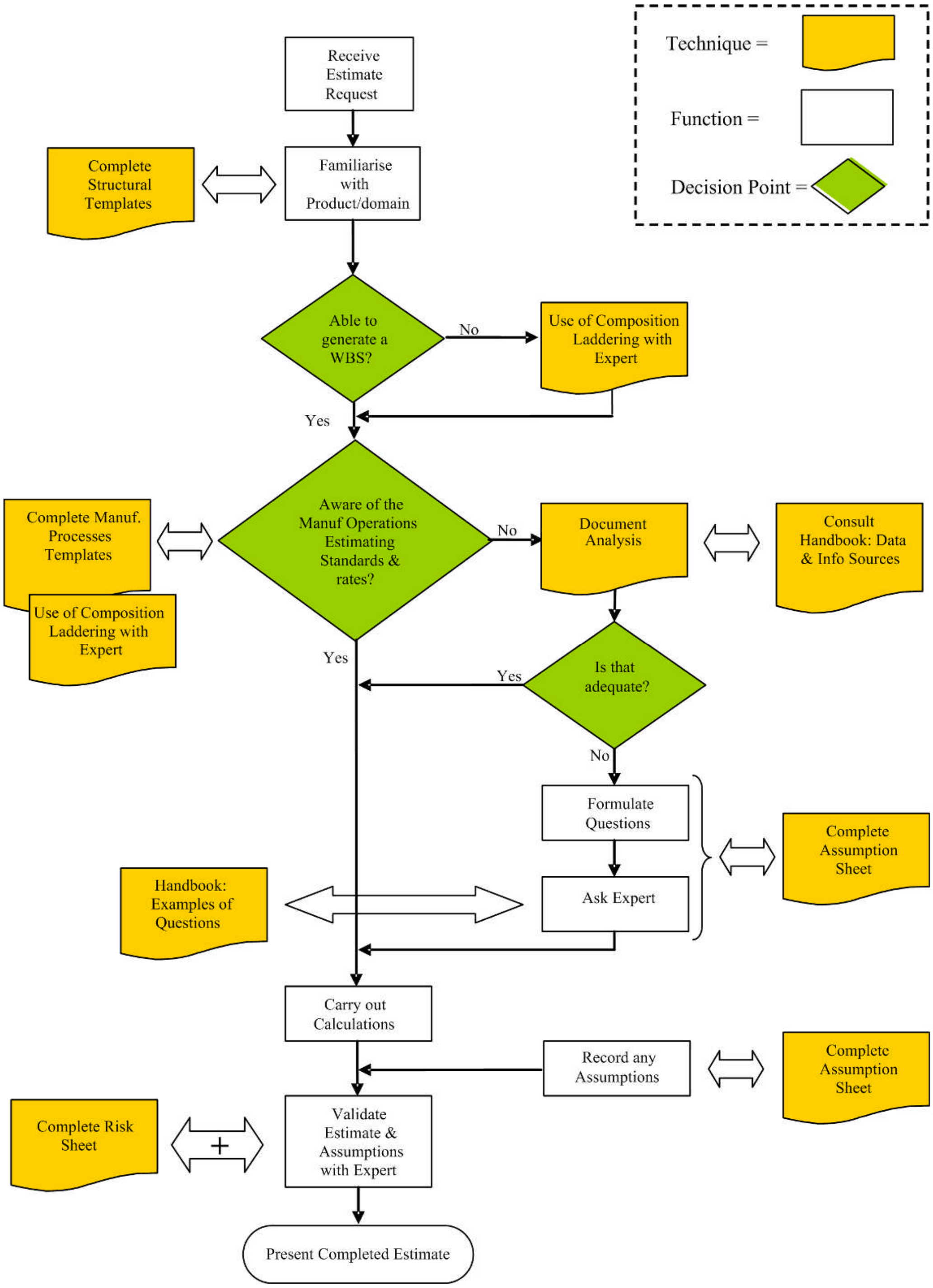


Figure 7.10 – KC² Methodology

The process starts with the cost estimator familiarising with the domain. Initially an understanding of the product, for which the cost estimate is developed for, needs to be gained. The cost estimator should complete the structural entity templates aiming at creating a complete picture about the product and the manufacturing processes involved. If the cost estimator does not have available a product breakdown, then s/he could apply the composition laddering technique for capturing this information from an expert.

The next step involves the cost estimator filling in the manufacturing process templates, and their associated fields. Document analysis could be used as a starting point to understand how a part is manufactured, what are the manufacturing operations and materials usage. The cost estimator could consult the tables presenting the sources of knowledge, to get a feel of where documents as such could be found. In the case where the available information and documentation is not enough to obtain all the knowledge necessary, the cost estimator should approach an expert. The fields of the templates should guide the cost estimator in terms of the knowledge requirements for developing the cost estimate. The generic questions of the templates could be used in order to ask the right questions. The assumptions sheet is used to record any additional issues, either in terms of assumptions made, or point where the cost estimator faces difficulties. This process is iterative until the cost estimator has captured all the knowledge essential in developing the cost estimate.

Once all the knowledge and data associated with that cost estimate have been captured, then the cost estimator can proceed at producing the cost estimate. That would involve the undertaking of all the numerical calculations, by utilising the knowledge captured within the templates. Upon completion of the cost estimate the cost estimator should complete the risk sheet. Following that all the assumptions made, as well as the templates filled, need to be presented to the related SMEs for validation. Once the SMEs verify that the cost estimate is based on correct and valid data, then the cost estimator could disseminate the results of that estimate. All the templates and sheets of the KC^2 methodology need to be included in the cost estimate report. That would provide transparency as to the calculations within the cost estimate, as well as some form of traceability as to the knowledge sources that were utilised.

7.3.2 Proposed Framework

As presented earlier, the findings of Chapter 5 were implemented within a tool that cost estimators can use for assessing and quantifying the quality of a cost estimate. The process of applying the tool, as part of the cost estimate development activity, was incorporated into an overall framework. The resulting framework structure is presented in Figure 7.11.

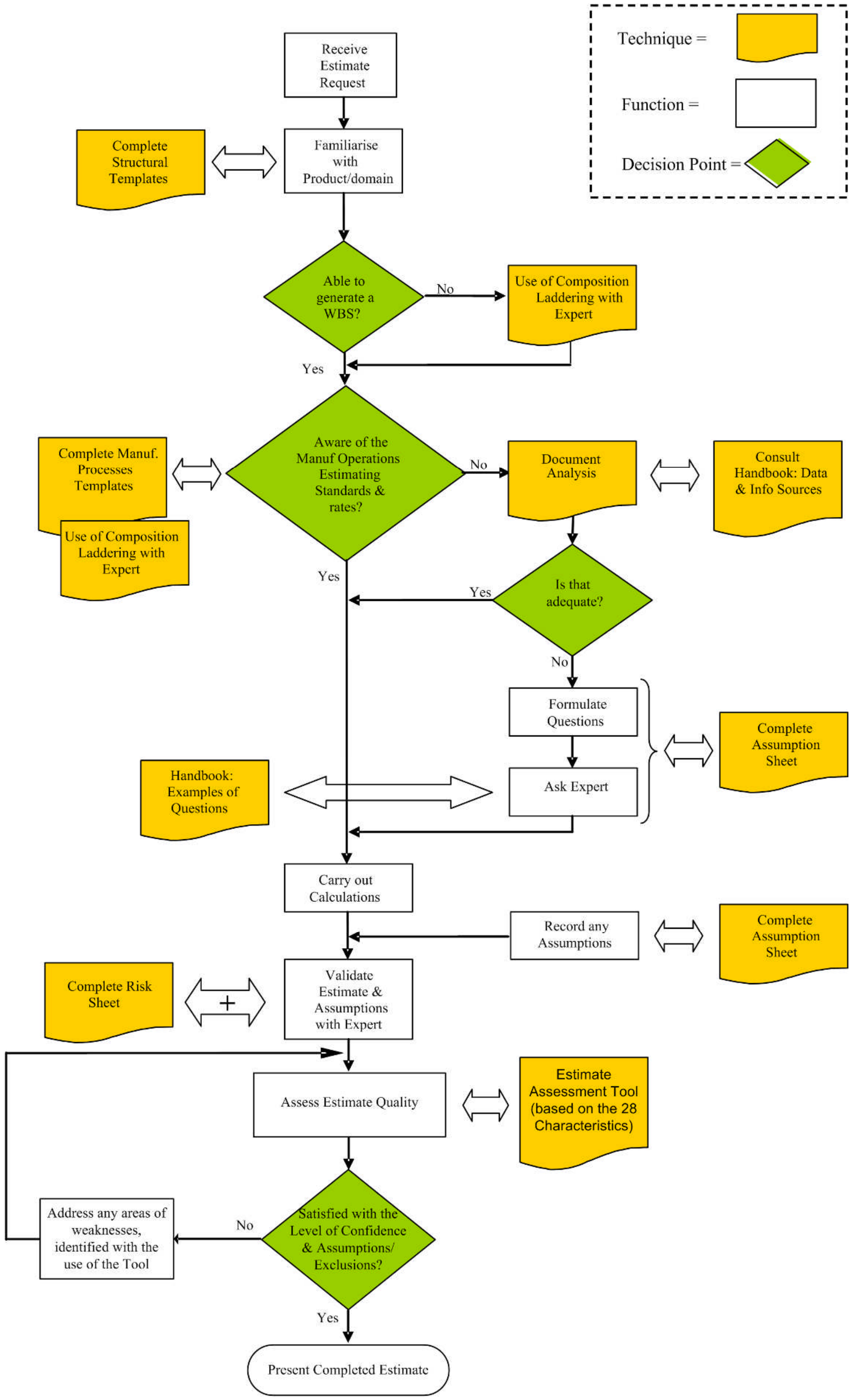


Figure 7.11 – Proposed Framework Structure

The framework consists of two distinct parts: a) the KC^2 methodology and b) the tool for assessing the quality of cost estimates. The KC^2 methodology focuses on the aiding a novice cost estimator in capturing all the knowledge required in developing a cost estimate. When the estimate has been completed, the tool developed in Chapter 6 would be applied in order to assess the quality of the cost estimate, and identify any potential areas of weakness of that estimate.

The next stage in this study involved the application of the proposed framework, in the form of a case study, in order to test its effectiveness.

7.3.3 Design of Experiment

In this Section, a description is provided regarding the approach followed in applying the framework in three case studies in order to test its fitness for use. The selection of the cases was based on both the available support to the researcher and the type of context of the cases to this study's overall context.

Once rapport was established with a particular organisation where the case study would take place, a product was selected for which a cost estimate already has been developed for, in the past by an expert cost estimator. The novice, who in this study is the author, would produce a cost estimate for that product following the proposed methodology. The novice would carry out the estimate based on the same conditions, and utilising the same tools and resources that the experts had used in carrying out their estimate.

At the end of the exercise a de-briefing workshop session would take place, where the expert would present their estimate to the novice, and compare his work to the novice's work. In addition, during this session the expert would validate the novice's use of data, as well as any assumptions that the novice made. Figure 7.12 presents the process followed in carrying out each case study.

The author believes that if the novice utilises all the data, tools and recourses that an expert had used for estimating the cost of a particular product, s/he will produce an estimate that is close enough to the expert's estimate. What it may potentially lack is

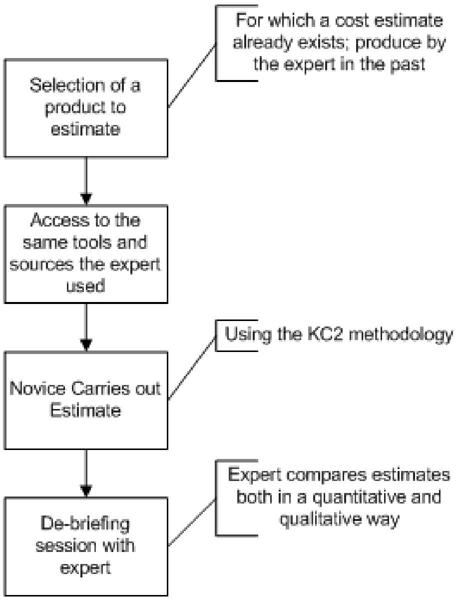


Figure 7.12 – Design of Experiment for the Case Studies

a level of quality, which could be found in the expert's estimate. A major portion of this difference could be attributed to the lack of knowledge by the part of the novice. Additionally the lack of experience would prevent novice estimators to realise whether their estimates are of good quality or not, as well as undertaking the necessary steps in achieving that; while expert cost estimators could intuitively achieve that.

The application of the proposed methodology in a context-specific case study is presented in the following Section.

7.4 Case Study 1 – Fan Cowl Door

In the previous Section, the development process leading to the creation of proposed framework was presented. A case study was carried out where the framework was applied in developing a cost estimate for an aerospace product. In this section, the author presents the case study, as well as the initial findings observed through the use of the framework.

7.4.1 Introduction to the Case Study

The estimate that the Novice was required to carry out was a detailed estimate of a Carbon Composite (CC) Fan Cowl Door, in response to an estimate request (presented in Appendix C.1). More specifically the recurring (manufacturing and production) cost was required to be estimated. A cost estimate based on the same estimate request has been already, at the time, developed by the expert. This estimate did not become available to the novice at the start of the case study, but only when the novice had completed his cost estimate. The author was the novice cost estimator throughout this case study. The expert's background lies in the cost estimating and contracts, of mechanical hardware products within the aerospace industry. He has approximately 30 years of experience in cost estimating, and he held a senior managerial position.

The Fan Cowl door is part of the engine nacelle, mounted on the engine pylon on the left and right side of an engine, and its main purpose is to allow easy access to the components mounted on the engine for routine maintenance operations. There are generally two doors per nacelle (so consequently two doors per engine) and there are various configurations depending on engine position and size. Figure 7.13 shows a Fan Cowl Door as found in an under-wing pylon configuration; which it is typical of many commercial aircrafts produced (for example, all latest Airbus & Boeing civil aircraft use this exact configuration).

Figure 7.13 – Illustration of a Typical Fan Cowl Door (permission granted by GKN Aerospace)

The Fan Cowl Door selected to produce a cost estimate for, is very similar to the one presented in Figure 7.13. A few key characteristics of the Fan Cowl Door selected in this case study, are that the door is primarily manufactured using carbon composite materials, the completed door consists of four hinges on the top and four latchets on the bottom (in the same way to the door exhibited in Figure 7.13). In addition, there are three access doors (used to access/check routine maintenance parts of the engine without the need of opening the whole door) and finally the door assembly consists of two 'hold-open' rods which are used to lock the door in an open position when required.

7.4.2 Application of the Methodology - Results

Following the KC^2 methodology, the first step was to define a product breakdown structure (PBS). The PBS was derived by the novice through an analysis of the provided of a typical Bill of Materials (presented in Appendix C, Figure C.4), as well as the supplied diagrams and drawings. Upon completion, the structure was presented to the expert for validation, making sure that the novice's understanding of the product is correct. The resulting product breakdown structure is presented in Figure 7.14. As a result, the estimate structure was based on this hierarchical structure.

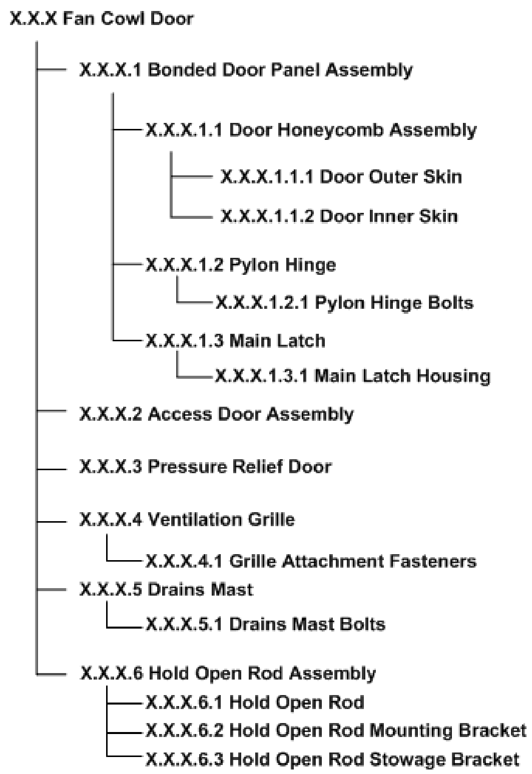


Figure 7.14 – Illustrated PBS for the Fan Cowl Door

Following the steps of the proposed methodology, the author started filling-in the templates based on the information that he has been provided. A number of documents were provided to the novice by the expert; documents which the expert have used in order to develop his estimate. The novice utilised documents provided to him, such as BOM for similar products, part's diagrammatic pictures and engineering drawings, in order to extract any information required by the templates' fields. Such documents enabled the novice in understanding the make-up of those parts, their function, dimensions, and so on. Documents which were made available to the novice are presented in Appendix C, Section C.1.

Following the familiarisation of the novice with the task, the estimate cover sheet was filled-in with all the available information at the time. This included labour rates, production quantity and any other overall estimate considerations. The estimate cover sheet for the Fan Cowl Door estimate is presented in Figure 7.15.

Estimate Cover Sheet								
Estimate/RFQ	Fan Cowl Door estimate							
Estimate Request Description (Scope)	Estimate the unit recurring cost for the Fan Cowl Door							
Production/Schedule Details	Production Quantity	500 Production A/C => => ~2,000 units						
	Production Rate/Schedule	Production Cycle 10–15 years						
Wrap/Labour Rates			Year	2005	20..	20..	20..	20..	20..
	Types of Wrap/ Labour Rates	Composite Manuf	[redacted] $/hr					
		Assembly	[redacted] $/hr					
		HP Autoclave	[redacted] /m²					
		LP Autoclave	[redacted] /m²					
Economic Conditions	Inflation	N/A						
	Currency rates … to … (If Applicable)							
	Other Conditions, Mark-ups and additional costs							
	- Costs to be based on 2005 EC - U.S. Currency to Quote ($)							
Other Estimate Considerations								
Information Source	- Estimate Request & Expert brief							
Management	Author	E. Loudos						
	Date	[redacted]						
	Validation Status							

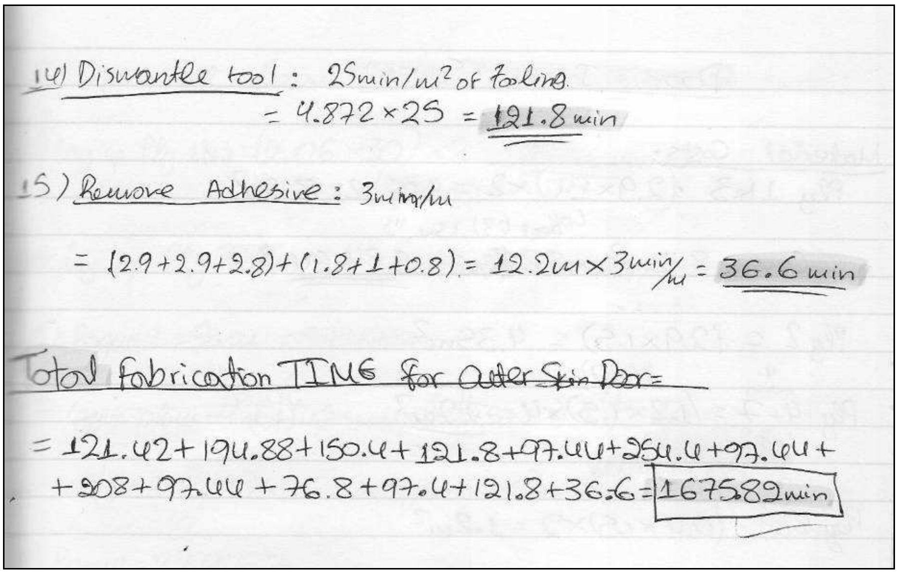
Figure 7.15 – Estimate Cover Sheet for the Fan Cowl Door Estimate

Figure 7.16 presents the structural entity template for the access panel outer skin. The rest of the templates completed by the author during the course of the case study, are presented in Appendix C, Section C.1.

Structural Entity		
Name	**Access Panel outer skin**	
Function(s)	It is part of the sandwich bonded access panel door structure. It also provides a smooth outer surface.	
Description	The access panel door is used on the Fan Cowl Door, in order to provide easy & quick access for routine maintenance; so the engineer would not have to open the whole fan cowl door.	
Dimensions/Drawing	The Access panel door is square in size with the following dimensions: 0.4m height and 0.5m length. So the Outer skin is going to have the same dimensions.	
Entity Source	Manufactured in-house	
Method of Manufacture	**Name**	Composite Laminate
	Description	The outer skin is made from layers of carbon fibre. They are pre-impregnated and they are lay on a tool in order to form the shape. After they are vacuum de-bulked and cured at High Pressure in an Autoclave.
Information Source	Mr. [redacted]	
Related Parts	**Parent**	Access Door Panel
	Child	None
Related Operations Characteristics	1. Lay up skin plies 2. Cure at High Pressure	
Management	**Author**	Evaggelos Lavdas
	Date	[redacted]
	Validation Status	Validated

Figure 7.16 – Structural Entity Template for the Access Panel Outer Skin

The novice carried out all the cost estimate calculations, covering all the areas that he was familiar, and/or had knowledge about, at that point in time. The various calculations were carried out manually, summarised in the end into an Excel spreadsheet. An example of such calculations is the estimation of the total fabrication time for the Outer Skin Door, presented in Figure 7.17. The effort required for each individual operation was manually calculated by the novice, based on the metrics identified. Following that, the individual times were summarised in order to come up with the total fabrication time. The same process was followed regarding the materials requirements for each operation.



14) Dismantle tool: 25min/m² of tooling
= 4.872×25 = 121.8 min

15) Remove Adhesive: 3min/m
= (2.9+2.9+2.8)+(1.8+1+0.8) = 12.2m × 3min/m = 36.6 min

Total fabrication TIME for Outer Skin Door=
= 121.42+194.88+150.4+121.8+97.44+254.4+97.44+
+208+97.44+76.8+97.4+121.8+36.6 = 1675.82 min

Figure 7.17 – Example of Outer Skin Door Fabrication Time Calculations

A summary of the Fan Cowl Door cost estimate is presented in Figure 7.18. The costs presented in the Figure have been factored due to commercial sensitivity issues.

When the novice felt that he addressed all the areas of the cost estimate, he approached the expert in order to present his work. Initially all the calculations, together with any assumptions made, were presented to the expert. The expert reviewed the assumptions made by the novice and the overall estimate. He then proceeded to comment on the differences, in terms of approach and/or assumptions made, between his estimate and the novice's estimate. After reviewing each part of the novice's estimate, the expert expressed that he was satisfied with the novice's work.

The next stage involved the direct comparison of the actual costs in the two

Level	Description			Cost ($)	Accum. Cost	Qty/ door
1	**Fan Cowl Door**					
1.1	Bonded door panel Assembly				*14078.02*	1
		Material Costs		205.436		
		Composite Manufacturing		740.3953333		
		HP curing		0		
		LP curing		413.6		
1.1.1	Door Honeycomb assembly			0	*1791.41*	
		Material Costs		0		
			LD core	379.61		
			HD core	46.2		
			Foam Adhesive	154.88		
		Composite Manufacturing		797.1186667		
		HP curing		0		
		LP curing		413.6		
				0		
1.1.1.1	Door Outer Skin			0	*6129.20*	
		Material Costs		2483.712		
		Composite Manufacturing		2611.486167		
		Assembly		0		
		HP curing		1034		
		LP curing		0		
1.1.1.2	Door Inner Skin			0	*4797.98*	
		Material Costs		1652.904		
		Composite Manufacturing		2111.074167		
		Assembly		0		
		HP curing		1034		
		LP curing		0		
1.2.1	Pylon hinge			0		4
			Material Cost	277.2	*277.20*	
			Machining Cost	0	*0.00*	
1.2.1.1	Hinge bolts			73.92	*73.92*	24
1.2.2	Main latch			528	*528.00*	4
1.2.3	Main latch housing			484	*484.00*	4
1.2	Access door Assembly			0	***429.56***	1
		Material Costs		0		
			Plies	47.52		
			LD Honeycomb	46.75		
			Film adhesive	5.06		
		Composite Manufacturing		100.3566667		
		Assembly		33.363		
		HP curing		0		
		LP curing		22		
1.2.1	Access Panel Outer Skin			0		
		Material Costs		47.52		
		Composite Manufacturing		71.995		
		Assembly		0		
		HP curing		55		
		LP curing		0		
1.4	Ventilation grille			48.4	*48.40*	1
1.4.1	Grille attachement fasteners			12.76	*12.76*	20
1.5	Drains mast			170.5	*170.50*	1
1.5.1	Drains mast bolts			11.55	*11.55*	6
	Seals			0	*174.68*	1
		Material Costs		170.28		
		Assembly		4.4		
10	Seal retainers			0	*164.86*	1
		Material Costs		39.732		
		Sheet Metal Manuf		125.125		
		Assembly		0		
17	Hold open rod			433.4	*433.40*	2
18	Hold open rod mounting bracket			59.4	*59.40*	2
19	Hold open rod stowage bracket			61.6	*61.60*	2
22	Latch mounting bolts			61.6	*61.60*	32
24	Seal retaining fasteners			223.3	*223.30*	350
25	Filler			30.8	*30.80*	1Kit
26	Primer paint			57.2	*57.20*	2L
27	Finish paint			37.4	*37.40*	1L
			Total Cost (excl. As	**17998.948**	*Dollars*	

Figure 7.18 – Fan Cowl Door Cost Estimate Summary

estimates. The Expert looked at the estimate developed by the novice and started to comment on the similarities and differences found. Table 7.4 presents the results from the comparison between the two estimates. It has to be noted that the actual numbers have been factored due to commercial sensitivity issues. The overall 'rolled-up' cost for the Fan Cowl Door was underestimated by 2.23% compared to the Expert's estimate. In addition, the unit cost just for the Bonded Assembly is presented, due to the reasons that the expert initially focused on comparing the two estimates at this level of decomposition. The difference in values at the Bonded Assembly level was found to be 0.42%.

Table 7.4 – Comparison of Estimates' Results, Between the Expert and the Novice

	Novice	Expert	Difference
Material Costs for Bonded Assembly	$ 4,922.7	$ 5,233.8	-6.32%
Manufacturing Costs For Bonded Assembly	$ 9,155.2	$ 8,903.4	2.75%
Unit Cost for Bonded Panel Assembly (Sum)	*$ 14,077.9*	*$ 14,137.2*	*-0.42%*
Total Unit Cost (Sum; excl. Assembly)	**$ 17,998.9**	**$ 17,597.8**	**2.23%**

There are differences between the two estimates, when individual elements within the estimates are analysed. For example in a situation where the Novice was not given concise information he had to make assumptions in order to continue his task. Assumptions like that could be simply 'what is the time required to lay carbon fabric'. This explains the small differences identified in terms of the values within the estimate. However these assumptions were presented to the expert, who verified them as being very close to reality.

No significant differences were identified during the comparison of the novice's and expert's estimate. The only difference, worth investigating, was the 6.32% underestimation from the part of the novice of the material costs of the bonded assembly. Under closer examination by the expert, it was identified that the novice did not account for the cost of a particular 'bought' part. This was due to that reason that it was not included neither in the BoM, nor in the supporting documentation available at the start of the task.

As an additional measure of cross-checking the results, the expert analysed the ratio of the total material cost versus the total manufacturing cost. The material cost accounted for around 45% of the total product cost while the manufacturing cost around 55%. The Expert commented that this ratio is what he would expert, according to his experience, for this type of product.

7.4.3 Knowledge Captured – Overall Analysis of Results

At the end of the exercise, a de-briefing session took place with the expert where the novice presented his cost estimate along with all the templates and any other supporting documentation. The expert validated the contents of the templates along with any assumptions made by the novice regarding the produced cost estimate.

The use of the templates, to drive the elicitation process regarding the data and information needed by the novice cost estimator in order to carry out the cost estimate, has led to the capture of tacit knowledge (from the expert). Knowledge as such was not found in any of the documentation provided to the novice (the same documentation that the expert utilised when he developed the same estimate), but is found in the expert's head. It has been acquired through years of experience in the particular domain. An example of such knowledge was that the tool area is almost equal to the part area plus an additional 20% of the part area. This is a rule of thumb, that based on experience it has been found to stand true. This is the sort of knowledge that it is not explicit, and a novice would not be able to find within documentation.

Figure 7.19 illustrates a snapshot of the 'Access Panel' structural entity template, providing an example of knowledge captured by the novice. It provides a description of how the skin of the panel is manufactured.

Entity Source	Manufactured in-house	
Method of Manufacture	**Name**	Composite Laminate
	Description	The outer skin is made from layers of carbon fibre. They are pre-impregnated and they are lay on a tool in order to form the shape. After they are vacuum de-bulked and cured at High Pressure in an Autoclave.
Information Source	Mr. [redacted]	
Related Parts	**Parent**	Access Door Panel
	Child	None
	1. Lay up skin plies 2. Cure at High Pressure	

Figure 7.19 – An Example of Knowledge Captured in the Structural Entity Template

Figure 7.20 illustrates a snapshot of the Assumptions sheet, providing an example of knowledge captured by the novice. The knowledge captured has to do with the application of one of the estimating standards regarding the autoclave process. The novice was not sure how to apply the estimating standard, in terms of calculating the part surface area.

4	When the Novice started making calculations for the Autoclave curing the only information that he was given was the cost per m2 of part. However he was not sure whether he should consider the area of only one side of the part, or the total area.	The assumption was made to take into account both sides of part.	When it comes to applying the Warp rates for the autoclave do I take the area of one side of the part, or of both sides?	The Expert said that you take the area of only one side. The Novice went back to the estimate and corrected the autoclave costs.

Figure 7.20 – An Example of Knowledge Captured in the Assumptions Sheet

Upon completion of the estimate, the next step was to assess the quality of the novice's cost estimate. The estimate assessment, using the tool presented in Chapter 6, is presented in the following Section.

7.4.4 Estimate Assessment Using the CEQA Tool

Upon completion of the cost estimate the author used the CEQA tool in order to assess how good his estimate was, in collaboration with an expert. A subjective perception for the Fan Cowl Door cost estimate was agreed, having a value of 85%. The novice then proceeded in using the tool in order to find out whether the tool's result comes close to that subjective perception. The ratings which were provided against each characteristic within the tool are presented in Table 7.5.

Table 7.5 – CEQA Ratings for the Fan Cowl Door Estimate

	Questions within Tool (Characteristics)	User Rating
1.1	Was the estimate based on a clearly defined scope of work?	4
1.2	Does the estimate appear to be updated for economic period?	4
1.3	Are the manufacturing quantity and productions rate(s) included with the estimate?	4
2.1	Are the results of the estimate presented in a simple and clear manner?	4
2.2	Does it appear that the estimate is based in a high level of technical detail?	3
2.3	Has a pre-defined process been followed in order to carry out the estimate (such as department procedures)?	3
2.4	Has the estimate/model been calibrated to the company's processes/rates?	4
2.5	Is there a Basis of Estimate (BOE) provided with the estimate?	2
2.6	Does the estimate summarize the main cost elements involved (eg. Breakdown into labour, materials, sub-contractor involvement etc)?	4
2.7	How complete/defined is the estimate's WBS/PBS/CBS for the type of estimate that is carried out for? (according to its purpose)	3
3.1	Have the rules and assumptions made been documented?	3
3.2	Have the data sources used been documented?	3
3.3	Has a report/documentation been submitted with the estimate, covering every aspect of it?	2
4.1	Has the estimate been based on valid quotes for purchased content?	4
4.2	Are the data & the information sources used considered to be credible and reliable (whether the sources are experts or databases/documents)?	3
4.3	Have other areas/departments of the business contributed to the estimate (such as inputs from Finance dpt, Operations etc)?	N/A

	Questions within Tool (Characteristics)	User Rating
5.1	Has an evaluation of potential risks taken place and the corresponding risks identified?	**1**
6.1	Have the cost drivers been identified (e.g. for cost reduction purposes)?	**3**
6.2	Was the estimate delivered on time?	**4**
6.3	Do you think the choice of cost estimating method and the effort spent on the estimate is appropriate to its final use?	**4**
6.4	Is there a relationship to schedule, shown within the estimate?	**2**
7.1	Has the estimate been reviewed by peers?	**4**
7.2	Has the supplier (or other interested parties) bought-in the process/model?	**4**
7.3	Have the assumptions made been validated by a subject matter expert?	**4**
7.4	Is the estimate accurate (specific to the type of estimate/business need)?	**3**
7.5	Has the estimated cost been benchmarked against industry norms (like carrying out a market study of similar products)?	**1**
7.6	Have any additional cost estimating techniques been employed to cross check; or has the estimate's output been checked against an existing calibrated/proven cost model?	**N/A**
7.7	Is it possible to check the estimate, or part of it, against a known cost (for example, a past 'similar to' estimate)?	**4**

Based on the assessment of the Fan Cowl Door cost estimate using the tool, the indicated result was found to be 81.08%. The indicated value was very close to the perceived value, thus both the author and the expert were happy with the tool's result.

Following an analysis of the ratings provided to the characteristics within the tool, the overall result was found to be at a satisfactory level; with the majority of the characteristics having attracted high ratings. However, there are some suggested areas for improvement that were identified through the use of the tool, and those were:

- Report/Documentation submitted with the estimate – Although the process followed by the novice was documented in the various templates of the methodology, a report was not prepared due to time constraints.
- Risks – Although the novice spent some time in identifying some potential risks, a more detailed risk identification process did not take place.
- Estimate result benchmarked against industry norms – This characteristic was partially satisfied. Industry norms were not available to the novice for comparison purposes. However, some abstract data regarding aerospace composite structures were used to benchmark the estimate.

These areas of potential improvement have also been captured in the detailed results sheet. Figure 7.21 presents the detailed results sheet for the Fan Cowl Door estimate, showing the 7 main categories and how their individual score.

Detailed Results for the Estimate Assessment

	Category	Result
1	Estimate Purpose & Conditions	100.00%
2	Estimate	82.53%
3	Documentation	67.21%
4	Data & Knowledge Utilised	86.54%
5	Risk Identification	25.00%
6	Miscellaneous	83.45%
7	Estimate Validation	82.79%

Figure 7.21 – CEQA Detailed Results Sheet for the Fan Cowl Door Estimate

Both the author and expert felt that the tool's result is representative of the cost estimate under considerations. The identified areas of weaknesses were expected, due to the reasons provided earlier on in this section.

7.4.5 Observations Regarding the Use of the Framework

The application of the framework on an industrial case study was presented. Throughout the case study, the author undertook the role of a novice cost estimator requested to develop an estimate for an aerospace product. The author at the time of the case study had a theoretical understanding of cost estimation and its principles, however he lacked of any real experience in developing a cost estimate for a real product. In addition, his understanding of the domain and the manufacturing processes (carbon composites) was limited at the time of the study. Thus, the author could be described as a true novice while undertaking the task.

With respect to the KC^2 methodology, the use of the structured templates has helped the novice in knowing what data were required in order to develop the cost estimate. The novice utilised all the documentation provided by the expert in order to gain an initial understanding of the domain and the task at hand, as well as for filling-in the fields of templates as much as possible. The generic questions accompanying the templates helped the novice to limit his questions to the expert to the essential knowledge required in developing the cost estimate. The KC^2 methodology has addressed the weaknesses identified with other KEL methodologies, as presented in Chapter 2.

Every time the novice got to a point where he faced a difficulty and the expert was not available for questioning, he would note down his question (or assumption) in order to ask the expert at a later stage. In this context, the assumptions sheet was particularly useful in keeping a record of all the assumptions, point that the novice got stuck, as well as any answers from the expert. As a result, the assumptions sheet led the novice capture knowledge from the expert; the kind of knowledge which is not explicit and could be found in the available documentation, but is rather based on years of experience in the domain area.

The use of the quality assessment tool allowed the novice to identify the areas of weaknesses in his estimate. The areas of weaknesses highlighted by the tool were indeed areas that required some further work. The tool's indicative value regarding the quality of the cost estimate was found to be realistic and representative of the actual effort that went into developing the estimate. The author felt that the use of the tool could help novices in concentrating on areas of weaknesses; and seek help from an expert regarding those areas, thus complementing the KC^2 methodology in its application.

In summary, the author was satisfied with the effectiveness of the framework and with the expert's positive feedback. The templates of the methodology were found to address all the areas related to the development of the cost estimate. In addition, the use of the tool in assessing the quality of the novice's estimate, at the end of the exercise, shown that the estimate itself satisfies the majority of the inherent characteristics of a good quality cost estimate. Areas for improvement have also been identified through the use of the tool.

7.5 Summary & Key Observations

In this Chapter, the development of the KC^2 methodology has been presented. Additionally, it was demonstrated how the methodology could be used in conjunction with the Quality Assessment Tool, and form a framework. Such a framework could help novice cost estimators in eliciting all the required knowledge for developing a cost estimate, as well as providing them with a means of assessing and quantifying the quality of their end result.

In Section 7.1, the requirements for the development of the proposed framework were defined. It was apparent that the proposed methodology should address those top-level requirements, the cost estimating knowledge needs, as well as the fulfilment (to the highest degree possible) of the inherent characteristics of a good quality cost estimate (identified in Chapter 5).

In Section 7.2, the author presented the development of the KC^2 methodology. The development process was influenced by the findings of Chapters 4 and 5, as well as the knowledge gained by the author during the literature review. Initially, the author selected a number of available KEL methods, through a scoring matrix approach, which could be incorporated in the overall methodology. Following that, the rationale for the development of the structured templates was presented, along with a set of generic questions complementing the structured templates.

In Section 7.3, the completed methodology was presented consisting of all the elements described during its development (in Section 7.2). The proposed methodology was complemented by the use of the tool (presented in Chapter 6); in forming a complete framework that novice cost estimators could use in order to produce good quality cost estimates.

Finally in Section 7.4, the framework was applied on a case study where the author estimated the cost of a Fan Cowl Door following the steps of the proposed framework. Both parts of the proposed framework were found to be effective in both eliciting the required knowledge for producing the estimate and assessing the quality of that estimate upon its completion, respectively. Through the application of the proposed framework the novice was able to complete a cost estimate for the Fan Cowl Door to a satisfactory degree, close to an expert's level, by using the same tools and resources that an expert had utilised. In addition, the templates and sheets of the methodology allowed the novice to elicit and capture some key knowledge essential in completing the estimate to a satisfactory degree.

In summary, they key observations of this Chapter are summarised as:

- A KEL methodology was developed which could be used by novice cost estimators in guiding them through the process of developing a cost estimate in a subject domain they are unfamiliar with.
- The proposed methodology was integrated with the cost estimate assessment tool into a complete framework; which could effectively be used by cost estimators in developing good quality cost estimates, following a formalised approach.

In the following Chapter, two additional case studies are presented by the author in order to further test the applicability of the methodology into two different domains. The results of the additional case studies shall be used to gain increased confidence on the effectiveness of the proposed framework.

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CHAPTER 8 – FURTHER CASE STUDIES & FRAMEWORK VALIDATION

In Chapter 7, the development of the overall framework was presented along with its application on a case study carried out within an aerospace organisation. The case study results highlighted some areas of improvement; nevertheless, early results suggest that the proposed framework has aided the novice in carrying out the cost estimate with minimal supervision.

The aim of this Chapter is to further explore the effectiveness of the proposed framework, through its application on additional case studies. As a result, two case studies were carried out, one within an aerospace organisation and the other within an automotive organisation. Finally, a detailed account of the methodology validation process is provided.

A similar process, to the case study presented in Chapter 7, was followed in order to apply the framework on two additional case studies. It should be noted that the two case studies presented in this Chapter, are smaller in size compared to the first one. This was due to limited availability of time, resources and access to experts that the author faced at the time.

8.1 Case Study 2 – Rib Assembly

The case study presented in this Section was carried out in another aerospace organisation. The novice developed a cost estimate for a structural wing assembly, using the proposed framework.

8.1.1 Introduction to the Case Study

The case study was carried out following a similar approach to the first one. The author spent two weeks time in the collaborating organisation's cost estimating department. He developed a cost estimate utilising the same tools and resources that the expert had used in developing his cost estimate for the same product. The expert's background lies in the cost estimating and pricing of mechanical hardware, electronics and maintenance contracts within the aerospace industry. He has approximately 27 years of experience in cost estimating, and he holds a senior managerial position. This particular case study was selected, based on a joint decision between the author and the experts, for the following three reasons: 1) A completed estimate already existed for that product, 2) the cost estimate has been recently carried out by the expert, and, 3) the selected case included a product where it is exclusively manufactured within the collaborating organisation, consisting of both manufactured parts and assembly operations.

The product selected to base the case study on, has been the Rib Assembly, presented in Figure 8.1.

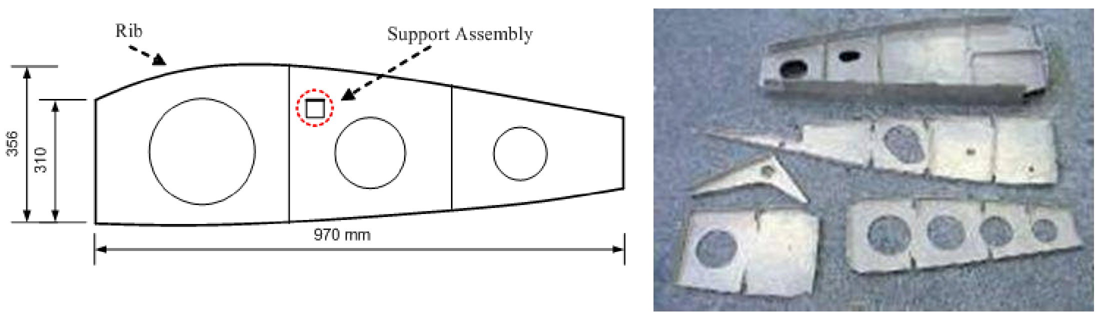


Figure 8.1 – Drawing and Picture of a Typical Rib Assembly

An estimate request was provided to the Novice for estimating the cost of production for a rib assembly, for the production period of 2008-10. This request summarises the RFQ that the expert had received from the customer, for quoting a price regarding this job. The cost estimate that the expert developed prior to this case study, was based on the customer's request. The details of the estimate request are summarised in Table 8.1. The work includes only the production (recurring) costs, as there is not any development involved and the majority of the tooling required for production already exists (or provided by the client) through an existing contractual agreement.

Table 8.1 – Estimate Request for the Rib Assembly

Estimate Request	
Production Quantity:	150 Units
Deliveries Rate:	50 Units/Year
Currency (to Quote):	In US Dollars ($)
Type of Price:	FIRM Price
Economic Conditions	2006 EC

Figure 8.2 presents the first sheet of the framework called the 'Estimate Cover Sheet'. This sheet is used to capture the overall estimate information, such as its

scope, economic conditions/assumptions applied and anything that the reader should know about this estimate in advance. Some of the fields have been blanked by the author, due to commercial sensitivities.

Estimate Cover Sheet								
Estimate/RFQ	**RFQ no. [redacted] – Rib Assembly**							
Estimate Request Description (Scope)	Estimate the production cost in response to a customer RFQ. There is no development involved, thus the recurring cost of production needs to be estimated. Breakdown the estimate results into labour, materials and packing cost elements.							
Production/Schedule Details	**Production Quantity**		Total work order of 150 units to be produced					
	Production Rate/Schedule		50 units per calendar year; Deliveries every 3 months					
Wrap/Labour Rates								
		Year	2008	2009	2010	20..	20..	20..
	Types of Wrap/ Labour Rates	Fabrication	[redacted] €	[redacted] €	[redacted] €			
		Assembly	[redacted] €	[redacted] €	[redacted] €			
Economic Conditions		**Inflation**	[redacted]%	[redacted]%	[redacted]%			
		Currency rates e to $ (If Applicable)	[redacted]	[redacted]	[redacted]			
	Other Conditions, Mark-ups and additional costs							
	G&A = [redacted]% Handling = [redacted]% Transportation = [redacted]%							
Other Estimate Considerations	No learning curves applied to this estimate. 100% assumed learning curve, due to continuing production contract.\ Quality Control is added at the end as a percentage; 7% of total recurring production effort.							
Information Source	Estimate information (production, scope of work etc) originated from estimate request; Economic info given by Finance.							
Management	**Author**		E. Lavdas					
	Date		[redacted]					
	Validation Status							

Figure 8.2 – Estimate Cover Sheet for the Rib Assembly Cost Estimate

In the following Section, the author presents the results of the case study.

8.1.2 Case Study Results

Following the KC[2] methodology, the first step was to define a product breakdown structure (PBS). The PBS was not explicitly present, and was extracted through analysis of the process plans, available for the product. Following that, the structure was presented to the expert to check its correctness. The resulting product breakdown structure is presented in Figure 8.3. The cost estimate was based on this hierarchical structure.

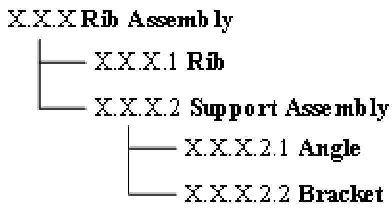


Figure 8.3 – Illustrated Product Breakdown into the Major Cost Elements

Once the main elements, which the product is composed of, were identified, the next step was to estimate the cost to manufacture each element. Following the KC^2 methodology, the templates were used by the novice to drive the elicitation process of the required information in order to complete the cost estimate for the Rib Assembly. The novice started the process of filling out the templates, initially based on the documentation that was made available to him. These were the kind of documents that the expert had utilised as well, while developing his estimate.

Figure 8.4 presents one of the structural entity templates for the Rib Assembly, as filled by the author while carrying out this case study. Templates for the lowest hierarchical entities of the rib assembly are presented in Appendix C, Section C.2.

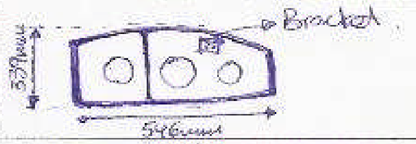
Structural Entity			
Name	Rib Assembly	P/N	classified [redacted]
Type (e.g. Ass., HW)	Assembly	Hierarchical Level	Level 3-X.X.X
Function(s)	Structural part of a wing primary structure for the [redacted] aircraft; load carrying component.		
Description	The rib assembly consists of the rib itself and a bracket attached to the rib, which is used to support auxillary lines.		
Dimensions/Drawing			
Entity Source	Assembled in-house		
Method of Manufacture/Assembly	Name	Rib Assembly	
	Description	The main rib is mounted on a tool/jig, where 5 holes are drilled & the support assembly is attached.	
Information Source	Expert A & Processes Master Plans		
Related Parts	Parent	None	
	Child	'Rib' and 'Support Assembly'	
Related Operations Characteristics	-Locate parts on tool -Drill holes & attach support Ass. -Paint Assembly to Specs. -Stamp P/N. see 'Rib Assembly' template		
Management	Author	E. Lavdas	
	Date	[redacted]	
	Validation Status	Validated by Expert	

Figure 8.4 – Structural Entity Template for the Rib Assembly

Figure 8.5 presents one of the 'Manufacturing Process' templates for the Rib Assembly, as filled by the author while carrying out this case study. Templates covering the rest of the manufacturing processes, associated with the rest of the entities of the Rib assembly, are presented in Appendix C, Section C.2.

While the novice was carrying out the estimate, a number of assumptions were made in order to compensate for the lack of his knowledge. Experts in the collaborating

Manufacturing Process				
Name	RIB ASSEMBLY			
Manufacturing Process Description	The Rib is located on tool where the support assembly is installed. The assembly is the primed and stamped.			
Tooling Requirements	**Tool(s) Life**	Last all duration of Production.		
	Tool(s) Price	NRC.		
Manufacturing Operations	**Name**	**Estimating Standard**	**Material Used**	**Wrap rates**
	1. Locate Parts on tool			ASS Rate
	2. Drill holes to size (x5)	0.0333/hole		– " –
	3. Disassemble & Deburr	0.0333/hole		– " –
	4. Clean for Glue Bond	S.P.		–
	5. Install all Items	0.166/assembly		– " –
	6. Touch-up Primer Epoxy	S.P.	Primer Epoxy	–
	7. Stamp Ink	0.1 hr/Stamp	Video Ink Jet	– " –
Materials Used	**Material Name**		**Material Price**	
	Rivets (x5)		0.06 $/5 rivets	
	Nutplate (x1)		2.299 $/nutplate	
	Primer Epoxy		1.072 $/assembly	
	Video Ink Jet		1.072 $/stamp	
Information Source	Master Plan & BOM & Expert.			
Related Processes	**Parent**	None		
	Child	'Machining High speed' & 'Support Assembly'		
Management	**Author**	[illegible]		
	Date	[redacted]		
	Validation Status	Validated		

Figure 8.5 – Manufacturing Process Template for the Rib Assembly

organisation were busy, and it was not possible to query them each time the novice faced a difficulty. As a result, assumptions were made, whereas possible, and recorded in the assumptions sheet (part of the KC[2] methodology). After the cost estimate was completed, the novice presented the assumption sheet to an expert for checking the correctness of those assumptions and for verification purposes.

The novice estimated the effort in undertaking all the manufacturing operations, and applied the appropriate wrap rates in order to convert the effort into cost. The engineering instructions were captured in the manufacturing process templates. Knowledge, regarding the manufacturing processes, originated mainly from the available process plans, as well as from discussions with SMEs. An example of the spreadsheet used to estimate the fabrication and assembly costs is presented in Figure 8.6. The results are factored due to commercial sensitivity issues.

		Description		Hours	Total Hr.Incl QC & SP	2008 Total Lab Eu	2009	2010
			Total:	4.454	**5.211**	341.24 €	356.78 €	373.03 €
X.X.X Rib Assembly				**0.659**		38.79 €	40.59 €	42.47 €
	1	Locate Parts of tool (cleco)		0.000				
	2	Drill holes to full size (for 5 rivets)		0.183				
	3	Dissassemble & Deburr		0.183				
	4	Clean for electrical bonding	sp					
	5	Install all items		0.183				
	6	Touch up fuel cell epoxy	sp					
	7	Stamp ink		0.110				
	8	Verify ink stamping		0.000				
	9	Stock parts		0.000				
X.X.X.1 Rib				**2.251187**		155.67 €	162.69 €	170.03 €
	1	Attach temp. metal tag		0.11				
	2	Set up machine (12 parts)		0.091667				
	3	*Machining 1st stage*		0				
	4	*Turn part at machine*		0				
	5	Machining 1st stage, turn & 2nd stage		1.683				
	6	Deburr		0.22				
	7	Drill holes (x4) at .098D		0.14652				
	8	Deburr holes (x4)		0				
	9	Remove machining mismatch	minimal					
	10	Clean for electrical bonding	sp					
	11	mask area (for electr. Conduct.)	sp					
X.X.X.2 Support Ass.				**0.43956**		25.87 €	27.07 €	28.33 €
	1	Locate & Clamp angle on the bracket		0				
	2	Drill & ream holes (x4)		0.14652				
	3	Dissassemble & Deburr		0.14652				
	4	Locate & hold clamp on bracket		0				
	5	Drill & ream holes (x2)		0.07326				
	6	Dissassemble & Deburr		0.07326				
	7	Dry install 6 rivets		0				

Figure 8.6 –Example of Engineering Instructions for the Rib Assembly Cost Estimate

Figure 8.7 provides a graphical representation of the contribution of each part of the rib assembly towards the overall unit cost.

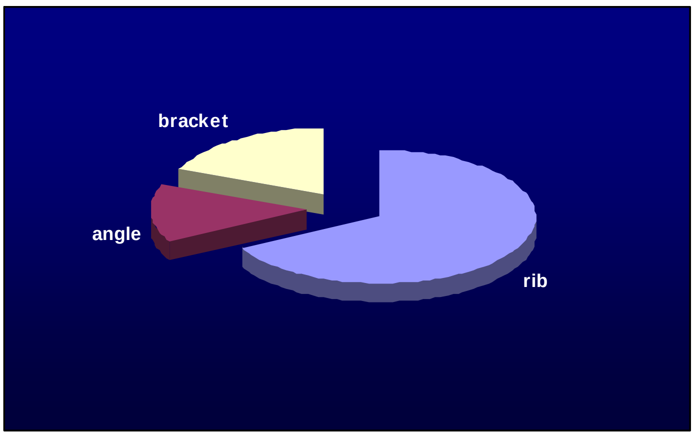


Figure 8.7 - Fabrication Man-hours per Unit

Figure 8.8 provides a graphical representation of the cost breakdown for the rib assembly. It was identified that the labour cost is the largest contributor to the overall unit cost, with the cost of materials following. The cost of tool maintenance is not significant.

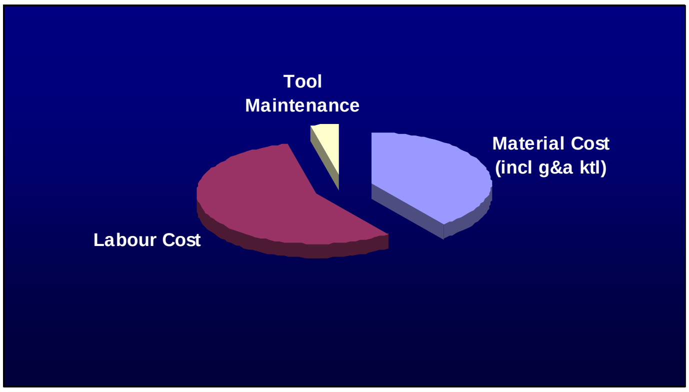


Figure 8.8 – Cost Breakdown into the Main Cost Elements

Unfortunately, detailed results (from the expert's estimate) do not exist for all the levels of the product breakdown structure. Thus, only the total values (at the Rib Assembly level) are directly compared. The only comparison details (from the expert's estimate), for this level of the estimate, is that the labour hours are a total of 5.28hrs. It is not possible to extract information about what percentage of the total time, corresponds to the 'assembly hours', 'quality control' or 'other special processes'. The results of the comparison are presented in Table 8.2.

Table 8.2 – Comparison of the Results between the Novice's and Expert's Estimated Production Hours

	Expert	Novice	Difference (%)
Total Assembly & Fabrication Hours (incl. QC & SP)	5.28 hr	5.211 hr	1.29 %
Assembly hours	-	1.098	-
Fabrication hours	-	3.356	-
Q.C. & S.P.	-	0.757	-

Table 8.3 presents the results of the comparison of the novice's and expert's cost estimates. The values represent Factory Cost (no profit margin or any other fees were applied). All costs were estimated in US Dollars ($), because the expert's cost estimate was based on this currency denomination. The exchange rates were captured in the estimate cover sheet, as provided by the finance department. It should be noted that all the cost estimate results are factored, due to commercial sensitivity issues.

Table 8.3 – Comparison of the Results between the Novice's and Expert's Estimates, for the 2008 Production Year

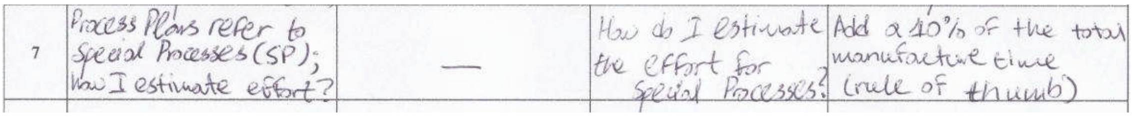
	Expert	Novice	Difference (%)	Reason for Difference
Total Cost	$ 825.54	$ 815.4	1.23 %	See below
Material Cost	$ 335.44	$ 324.83	3.16 %	An additional part has been added in the final BOM, accounting for the difference. When the older version of the expert's BOM is compared to the material cost estimated by the Novice, the result is the same. The novice was provided with an older version of the BOM
Labour Cost (including tool maint.)	$ 490.1	$ 490.57	- 0.1 %	There is an 0.069hrs difference between the expert's estimated hours and the novice's estimate. By comparing the results from the expert's estimate, it looks like the Fabrication rate has been applied for the whole of the 5.28 hours; while the Novice used the fabrication rate for the fabrication hour and the assembly rate for the assembly hours.

The results of the novice's cost estimate were in close proximity to the results found within the expert's estimate. The only significant difference in terms of the estimated values, was identified with regards to the cost of materials. Following the de-brief session with the expert (where the expert went through the novice's estimate and templates), it was identified that the reason for the variance in values was due to the fact that the novice used an older version of the BOM compared to the one that the expert had used.

In summary, both the novice and the expert were satisfied with the estimated costs. This demonstrates that the use of the KC^2 methodology, in conjunction with the knowledge acquired from an expert, enables a novice to produce a cost estimate comparable to an estimate that would be developed by an expert.

8.1.3 Identified Knowledge

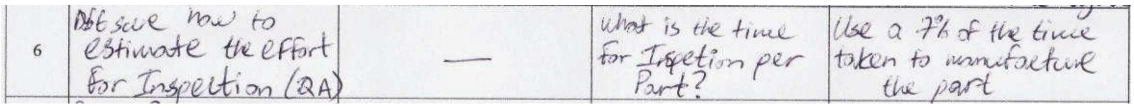
Throughout the course of the case study, the novice filled in the various templates and sheets of the KC^2 methodology. During the cost estimate development, the author analysed the Process Plans. He identified that a number of special processes would need to be undertaken, following the initial machining operations of the rib. However, the novice was struggling to estimate the cost of these processes. Upon questioning the expert, it was identified that as a 'rule of thumb' a 10% of the time taken to produce the unit is applied to account for the cost of these processes. Knowledge as such is not explicitly found in any of the documentation, and it has been developed through years of experience in that particular domain. The novice captured the expert's comments into the assumptions sheet. An example of knowledge captured within the assumptions sheet is presented in Figure 8.9.



7	Process Plans refer to Special Processes (SP); How I estimate effort?	—	How do I estimate the effort for Special Processes?	Add a 10% of the total manufacture time (rule of thumb)

Figure 8.9 – Snapshot of the Completed Assumptions Sheet

Similarly to the previous example, the author was not aware how much time it takes to carry out the Quality Inspection process for the machined parts. Upon questioning the expert, it was identified that again a percentage of the time taken to manufacture is applied on top of the unit cost, as a rule of thumb. Figure 8.10 presents the knowledge, as it was captured in the assumptions sheet.



6	Not sure how to estimate the effort for Inspection (QA)	—	What is the time for Inspection per Part?	Use a 7% of the time taken to manufacture the part

Figure 8.10 – Snapshot of the Completed Assumptions Sheet

The fully completed assumptions sheet is presented in Appendix C, Figure C.28.

8.1.4 Estimate Assessment using the Tool

Upon completion of the cost estimate, the author in collaboration with an expert would use the tool in order to assess how good his estimate was. As per the process described in Chapter 6, a subjective perception was given regarding the Rib Assembly cost estimate. The value of it was perceived to be 90%. The ratings that were provided against each characteristic within the tool are presented in Table 8.4.

Based on the assessment of the Rib Assembly cost estimate, the tool's indicated result was found to be 88.38%. The tool's result was very close to the perceived value, thus both the author and the expert were satisfied. The expert commented that he felt that the cost estimate developed by the novice reflects the result of the CEQA tool.

Overall the cost estimate appeared to fulfil the majority of the characteristics, against which it was assessed, to a satisfactory degree. Documentation was one of the areas

Table 8.4 – CEQA Ratings for the Rib Assembly Estimate

	Questions within Tool (Characteristics)	User Rating
1.1	Was the estimate based on a clearly defined scope of work?	**4**
1.2	Does the estimate appear to be updated for the economic period?	**4**
1.3	Is the manufacturing quantity and production rate(s) included in the estimate?	**4**
2.1	Are the results of the estimate presented in a simple and clear manner?	**3**
2.2	Does it appear that the estimate is based in a high level of technical detail?	**4**
2.3	Has a pre-defined process been followed in order to carry out the estimate (such as department procedures)?	**4**
2.4	Has the estimate/model been calibrated to the company's processes/rates?	**4**
2.5	Is there a Basis of Estimate (BOE) provided with the estimate?	**2**
2.6	Does the estimate summarise the main cost elements involved (e.g. Breakdown into labour, materials, sub-contractor involvement, etc.)?	**4**
2.7	How complete/defined is the estimate's WBS/PBS/CBS for the type of estimate that is carried out? (According to its purpose)	**4**
3.1	Have the rules and assumptions made been documented?	**3**
3.2	Have the data sources used been documented?	**3**
3.3	Has a report/documentation been submitted with the estimate, covering every its aspect?	**2**
4.1	Has the estimate been based on valid quotes for purchased content?	**4**
4.2	Are the data & the information sources used considered to be credible and reliable (whether the sources are experts or databases/documents)?	**3**
4.3	Have other areas/departments of the business contributed to the estimate (such as inputs from Finance dpt, Operations, etc.)?	**4**
5.1	Has an evaluation of potential risks been taken place and the corresponding risks identified?	**3**
6.1	Have the cost drivers been identified (e.g. for the cost reduction purposes)?	**N/A**
6.2	Was the estimate delivered on time?	**N/A**
6.3	Do you think the choice of cost estimating method and the effort spent on the estimate are appropriate to its final use?	**4**
6.4	Is there a relationship to the schedule, shown within the estimate?	**3**
7.1	Has the estimate been reviewed by peers?	**4**
7.2	Has the supplier (or other parties involved) bought-in the process/model?	**3**
7.3	Have the assumptions made been validated by the expert of a subject matter?	**4**
7.4	Is the estimate accurate (specific to the type of estimate/business need)?	**4**
7.5	Has the estimated cost been benchmarked against industry norms (like carrying out a market study of substitutes)?	**N/A**
7.6	Have any additional cost estimating techniques been employed to cross check; or has the estimate's output been checked against an existing calibrated/proven cost model?	**N/A**
7.7	Is it possible to check the estimate, or part of it, against a known cost (for example, a past 'similar to' estimate)?	**4**

that scored lower than the rest during the cost estimate assessment. Some areas for improvement were identified through the use of the tool, and these were:

- BOE provided with the estimate – The BOE was not prepared to a satisfactory level.
- Relationship to schedule – There was a relationship to the schedule shown within the estimate; it could have been more detailed though.

These areas of potential improvement were also captured in the detailed results sheet. Figure 8.11 presents the detailed results sheet for the Rib Assembly estimate, showing the 7 main categories and their individual score.

Detailed Results for the Estimate Assessment

	Category	Result
1	Estimate Purpose & Conditions	100.00%
2	Estimate	88.75%
3	Documentation	67.21%
4	Data & Knowledge Utilised	90.82%
5	Risk Identification	75.00%
6	Miscellaneous	89.02%
7	Estimate Validation	95.29%

Figure 8.11 – CEQA Detailed Results Sheet for the Rib Assembly Estimate

The tool did not identify any areas of weaknesses related to the 'data and knowledge utilised' category. The result of the assessment could imply that the cost estimate addressed and captured all necessary knowledge to a satisfactory degree. The author was satisfied that the use of the framework guided him in capturing all the necessary information required to develop the cost estimate. The tool's results partially reflect that.

8.2 Case Study 3 – Automotive

The case study presented in Section 8.1, took place within an aerospace setting. The case study presented in this Section, focused on the automotive industry, and more specifically on an automotive manufacturer of luxury sport cars. It should be noted that the manufacturer's production volume is low compared to other automotive manufacturers. Nevertheless, the way that the business works is very similar to larger automotive OEMs, where the majority of the parts are provided by multiple suppliers. The only difference to larger-size automotive OEMs is that there is a small portion of hand-finishing and customisation operations (usually applied to a number of interior parts).

8.2.1 Introduction to Case Study

An integral part of the duties of cost estimators within the organisation is to check that the suppliers' quotes are realistic; achieved by developing their own independent cost estimates about what they believe the part should cost. The nvice was asked to generate a should-cost estimate for an automotive part in order to analyse a supplier's quoted price. The part was an Airbag Trim Cover, part of the car's dashboard. This kind of part is manufactured externally by an automotive supplier. A cost estimate for this part was already developed by the expert prior to the case study. The expert's background lies in the cost estimating and target costing of mechanical hardware products within the automotive industry. He has approximately 26 years of experience in cost estimating, and he held a managerial position.

The Airbag Cover Assembly is held secure on the dashboard through six fixture holders. In the event of an airbag deployment, the trim has to detach from the dashboard in order for the airbag to inflate and deploy. At the same time injuries to the car passenger should be prevented, as a result of the airbag's explosive force.

Figure 8.12 presents a typical Airbag Trim Cover; both the upper and lower side of this trim are displayed.

(a) Front View (b) Rear View

Figure 8.12 – Upper and Lower Sides of the Airbag Cover Assembly

The design of the airbag cover assembly is simple in nature, having two main purposes: a) to allow a non-obstructing deployment of the passenger airbag (with the airbag well hidden underneath the dashboard) and b) at the same time follow the contours of the dashboard (aesthetics). The trim is composed of ABS plastic and is manufactured via injection moulding. The only additional parts to the manufacture of the actual cover are six metallic fixtures.

Figure 8.13 presents the 'Estimate Cover Sheet' for the Airbag Cover Assembly estimate. It should be noted that some of the fields within the template were blanked by the author, due to commercial sensitivities.

Estimate Cover Sheet							
Estimate/RFQ	'Airbag Cover Assembly' – Should Cost						
Estimate Request Description (Scope)	Prepare a should-cost estimate, in order to check a supplier's quote.						
Production/Schedule Details	**Production Quantity**	50,000 units (5years)					
	Production Rate/Schedule	10,000 units / Year					
Wrap/Labour Rates							
	Year	2006	2007	2008	2009	2010	20..
	Types of Wrap/ Labour Rates – Moulding	[redacted] €	Adjusted for Inflation				
	Assembly	[redacted] €					
	Moulding Machine Rate	[redacted] €					
Economic Conditions	**Inflation**	–	[redacted] %	[redacted] %	[redacted] %	[redacted] %	
	Currency rates … to … (If Applicable)	N/A	—				
	Other Conditions, Mark-ups and additional costs						
	G&A = [redacted] % Profit = [redacted] %						
Other Estimate Considerations	-Need to take into account the cost for Scrap Material (at [redacted] % of Manufacturing cost) -use Supplier Rates, when possible.						
Information Source							
Management	**Author**	E. Loudas					
	Date	[redacted]					
	Validation Status	Validated.					

Figure 8.13 – Estimate Cover Sheet for the Airbag Cover Assembly Cost Estimate

The results of the case study are presented in the following Section.

8.2.2 Case Study Results

Following the KC^2 methodology, the first step was to define a product breakdown structure (PBS). The PBS was identified through the use of the composition laddering technique, and analysis of the available engineering drawings. The novice made use of the provided probe questions in order to understand the make-up of the component. The resulting structure was presented to the expert for validation purposes. Figure 8.14 presents the PBS for the Airbag Cover Assembly.

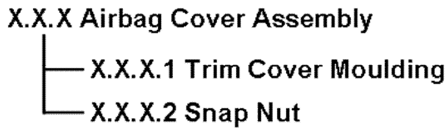


Figure 8.14 – Airbag Cover Assembly PBS

The next step was to estimate the cost to manufacture each element. Following the KC^2 methodology the templates were used by the novice to drive the elicitation process of the required information, in order to develop the cost estimate for the airbag cover assembly. The novice utilised documents that were made available to him; the same documents that the expert had used in developing his estimate. Documents as such included: engineering drawings of the product, a life-size model, company labour rates and some supplier technical specifications documents.

Figure 8.15 presents the structural entity template for the Airbag Cover Assembly.

Structural Entity			
Name	Airbag Cover Assembly	P/N	[redacted]
Type (e.g. Ass., HW)	Assembly (HW)	Hierarchical Level	X.X.X
Function(s)	Cover the Airbag unit (on the car's dashboard)		
Description	The airbag cover assembly is located on the dashboard, covering the passenger's airbag unit. It is supposed to be expelled, upon an airbag deployment.		
Dimensions/Drawing	see Part Drawings.		
In-house or Sub-contracted?	Sub-contracted		
Method of Manufacture/ Assembly	Name	'Trim Cover Assembly'.	
	Description	The trim is placed on fixture, and the inserts are placed on the moulded item.	
Information Source	Expert		
Related Parts	Parent		
	Child	'Trim Cover Moulding' & 'Snap Nut'.	
Related Operations Characteristics	see 'Trim Cover Assembly' template.		
Management	Author	E-Lados	
	Date	[redacted]	
	Validation Status	Validated	

Figure 8.15 – Structural Entity Template for the Airbag Cover Assembly

In addition, the Manufacturing Process templates were completed by the novice, making use of the accompanying questions for asking the expert, when required. Figure 8.16 presents the Manufacturing Process templates for the assembly of the airbag cover unit.

Manufacturing Process				
Name	Trim Cover Assembly			
Manufacturing Process Description	Fixings are initially placed manually on the 'Trim Moulding'; and then pressed tight into the cavities, by machine operation.			
Tooling Requirements	Tool(s) Life	N/A		
	Tool(s) Price	N/A.		
Manufacturing Operations	Name	Estimating Standard	Material Used	Wrap rates
	1. Locate Mould of Fixture	0.5min/part	—	Assembly
	2. Place Inserts in Mould	0.25min/insert	Snap Nut	Assembly
	3. Remove from Fixture	0.5min/Part	—	Assembly
Materials Used	Material Name		Material Price	
	(x6) Snap Nuts		20c/each	
Information Source				
Related Processes	Parent	N/A		
	Child	'Injection Moulding'		
Management	Author	G. Cardos		
	Date	[redacted]		
	Validation Status	Validated		

Figure 8.16 – Manufacturing Process Template for the Trim Cover Assembly

After the novice completed the cost estimate, and was satisfied with the assumptions made, the expert reviewed the novice's estimate. The validation process involved the expert comparing line by line the two cost estimates (his and the novice's), and querying the novice regarding various aspects of the estimate itself.

The novice estimated the effort in undertaking all the manufacturing operations, and applied the appropriate wrap rates in order to convert the effort into a cost. An example of the spreadsheet used to estimate the labour cost is presented in Figure 8.17. The results are factored due to commercial sensitivity issues.

	Description		minutes	Labour
		Total:	5.130	7.25 €
X.X.X Trim Cover Assembly			**2.710**	0.91 €
1	Locate Mold on Fixture		0.550	
2	*Manually place insterts on Mold (x6)*		*1.610*	
3	*Machine punches inserts firmly*		*0.000*	
4	Remove assembly from fixture		0.550	
X.X.X.1 Trim Molding			**2.420**	6.34 €
1	Clean die		0.275	
2	*Die Closes*		*1.375*	
3	*Material Injected*		*0.000*	
4	*Cooling process*		*0.000*	
5	*Eject from die*		*0.000*	
6	Remove from machine		0.220	
7	Trim excess material		0.550	

Figure 8.17 – Example of Engineering Instructions for the Airbag Cover Assembly Cost Estimate

Figure 8.18 provides a graphical representation of the contribution of each part of the Airbag Cover Assembly, towards the overall unit cost.

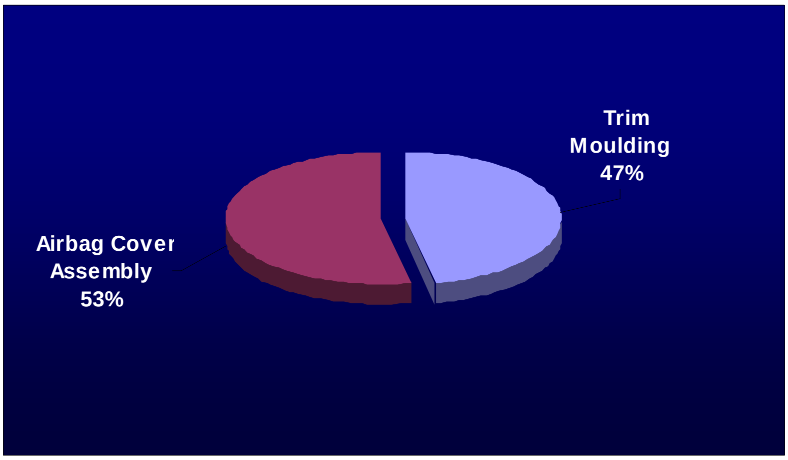


Figure 8.18 - Fabrication Man-hours per Unit

Figure 8.19 provides a graphical representation of the cost breakdown for the Airbag Cover Assembly, split in its main cost elements. As identified labour cost is the largest contributor to the overall unit cost, with the cost of materials following. Interestingly enough the split between labour cost and material cost is similar to the results of the Rib Assembly case study (nearly a 60/40 split as a rule of thumb).

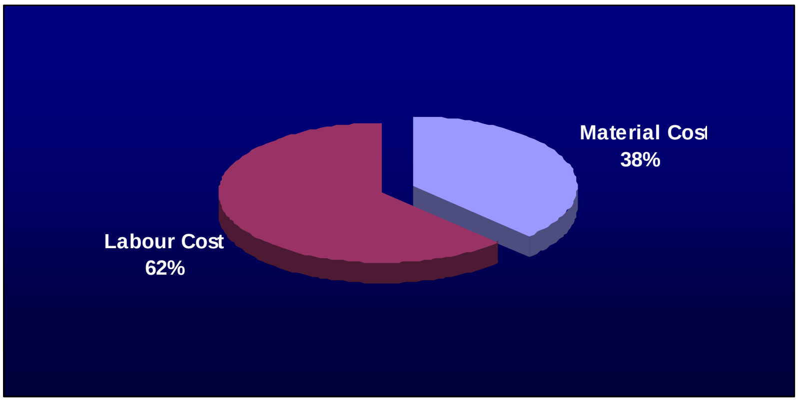


Figure 8.19 – Cost Breakdown into the Main Cost Elements

Table 8.5 presents a comparison of the novice's and expert's estimates in terms of hours estimated. A breakdown of the total manufacturing time is provided, showing the differences between the two estimates.

Table 8.5 – Comparison of the Results between the Novice's and Expert's Estimated Production Hours

	Expert	Novice	Difference (%)
Total Assembly & Fabrication Hours	**5.17 min**	**5.13 min**	0.77 %
Assembly hours	2.75 min	2.71 min	1.45 %
Fabrication hours	2.42 min	2.42 min	0 %

Table 8.6 presents the results between the estimates prepared by the novice and the expert, respectively. The values presented in the table represent factory cost only, excluding any fees and profit. Additionally, all values are factored by the author due to commercial sensitivity issues.

Table 8.6 – Comparison of the Results between the Novice's and Expert's Estimates

	Expert	Novice	Difference (%)	Reason for Difference
Total Cost	**€ 12.03**	**€ 11.99**	**0.33%**	
Material Cost	€ 4.37	€ 4.37	0.00 %	
Labour Cost	€ 7.30	€ 7.25	0.68%	Slight difference in assembly time calculated
Scrap/Setup	€ 0.36	€ 0.37	(2.7)%	Minimal differences in both scrap and set-up values

The results of the novice's estimate were in close proximity to the results found within the expert's estimate. The material cost estimated by the novice, was found to be exactly the same as the one estimated by the expert. This could be due to utilising the same kind of public resources in obtaining commercial material prices.

Both the novice and the expert assumed in their cost estimates the same material quantity value, provided by the available engineering drawings.

The cost of scrap was slightly different between the novice's and expert's estimate. That was due to the small difference in the labour cost values, since the value of scrap is driven by the unit cost. A slight difference was also identified with respect to the machine set-up cost values. The novice had calculated the total time to set-up the machine, divided by the batch quantity. The expert checked the numerical values in this calculation and found it to be correct; identifying that the small difference was due to rounding error.

8.2.3 Identified Knowledge

The use of the various templates and sheets, part of the proposed methodology, has resulted in capturing some key knowledge associated with the cost estimation of this particular kind of product. For example, the novice was not aware what the cost of scrap is and how to calculate it. As a result, an assumption was made and recorded in the assumptions sheet. At the end of the exercise, the novice presented the assumption to the expert to find out whether it is realistic. The response received by the expert, was also captured in the assumptions sheet. Figure 8.20 presents a snapshot of the assumptions sheet completed by the novice, with an example of knowledge captured.

Ass. #	Points where Novice got Stuck	Assumption Made	Question generated (if Applicable)	Expert's Response
1	Not sure what the scrap rate is.	3-4% of total material cost?		-The scrap rate should be around 2% of the unit cost (added on unit cost)

Figure 8.20 – Knowledge Captured in the Assumptions Sheet

Due to the fact that this part is manufactured by an external supplier, there weren't any internal company standards available regarding the time taken to carry out an injection moulding process for this part. As a result, the novice used publicly available generic estimating standards for injection moulding. The expert pointed the novice to the right direction in terms of identifying such resources. In addition, the novice did not have any knowledge about the material rates that he should apply. The expert provided him with a public source of commercial material rates that cost estimators tend to use in their estimates, within the organisation.

With regards to inflation rates, fixed inflation rates are provided to cost estimators by the organisation (forecasted at an organisation level). These rates were provided to the novice by the expert, since the expert had also utilised them during the development of his cost estimate.

8.2.4 Estimate Assessment using the Tool

Upon completion of the cost estimate, the author would use the tool in order to assess how good his estimate was, in collaboration with the expert. A subjective perception was provided regarding the Airbag Cover Assembly cost estimate. The value of it was perceived to be 85%. The ratings which were provided against each characteristic within the tool are presented in Table 8.7.

Table 8.7 – CEQA Ratings for the Airbag Cover Assembly Estimate

	Questions within Tool (Characteristics)	User Rating
1.1	Was the estimate based on a clearly defined scope of work?	4
1.2	Does the estimate appear to be updated for the economic period?	4
1.3	Is the manufacturing quantity and production rate(s) included in the estimate?	3
2.1	Are the results of the estimate presented in a simple and clear manner?	4
2.2	Does it appear that the estimate is based in a high level of technical detail?	3
2.3	Has a pre-defined process been followed in order to carry out the estimate (such as department procedures)?	3
2.4	Has the estimate/model been calibrated to the company's processes/rates?	3
2.5	Is there a Basis of Estimate (BOE) provided with the estimate?	2
2.6	Does the estimate summarise the main cost elements involved (e.g. Breakdown into labour, materials, sub-contractor involvement, etc.)?	4
2.7	How complete/defined is the estimate's WBS/PBS/CBS for the type of estimate that is carried out? (According to its purpose)	4
3.1	Have the rules and assumptions made been documented?	3
3.2	Have the data sources used been documented?	3
3.3	Has a report/docum. been submitted with the estimate, covering every its aspect?	1
4.1	Has the estimate been based on valid quotes for purchased content?	N/A
4.2	Are the data & the information sources used considered to be credible and reliable (whether the sources are experts or databases/documents)?	3
4.3	Have other areas/departments of the business contributed to the estimate (such as inputs from Finance dpt, Operations, etc.)?	N/A
5.1	Has an evaluation of potential risks been taken place and the corresponding risks identified?	0
6.1	Have the cost drivers been identified (e.g. for the cost reduction purposes)?	4
6.2	Was the estimate delivered on time?	4
6.3	Do you think the choice of cost estimating method and the effort spent on the estimate are appropriate to its final use?	4
6.4	Is there a relationship to the schedule, shown within the estimate?	N/A
7.1	Has the estimate been reviewed by peers?	4
7.2	Has the supplier (or other parties involved) bought-in the process/model?	4
7.3	Have the assumptions made been validated by the expert of a subject matter?	4
7.4	Is the estimate accurate (specific to the type of estimate/business need)?	4
7.5	Has the estimated cost been benchmarked against industry norms (like carrying out a market study of substitutes)?	3
7.6	Have any additional cost estimating techniques been employed to cross check; or has the estimate's output been checked against an existing calibrated/proven cost model?	N/A
7.7	Is it possible to check the estimate, or part of it, against a known cost (for example, a past 'similar to' estimate)?	4

Based on the assessment of the Airbag Cover Assembly cost estimate using the tool, the indicated result was found to be 82.5%. The indication value was very close to the perceived value, thus both the author and the expert were happy with the tool's result. The expert expressed that he was satisfied with the quality of the novice's work.

Overall, the cost estimate appeared to fulfil the majority of the characteristics, against which it was assessed, to a satisfactory degree. Some areas for improvement were though identified, through the use of the tool, and these were:

- Evaluation of Risks – The novice assumed that there are no risks, at the time of the estimate assessment, due to the product being sub-contracted. There was not enough time to discuss this further with the expert.
- Estimate based on similar-to products – The novice did not have any available resources to compare the part cost to any similar products.
- Report/Documentation submitted with the estimate – The documentation prepared to support the estimate was not extensive.
- BOE provided with the estimate – The BOE was not provided to a satisfactory level.

These areas of potential improvement have also been captured in the detailed results sheet. Figure 8.21 presents the detailed results sheet for the Airbag Cover Assembly estimate, showing the 7 main categories and their individual score.

Detailed Results for the Estimate Assessment

	Category	Result
1	Estimate Purpose & Conditions	91.84%
2	Estimate	82.90%
3	Documentation	59.42%
4	Data & Knowledge Utilised	75.00%
5	Risk Identification	0.00%
6	Miscellaneous	100.00%
7	Estimate Validation	95.91%

Figure 8.21 – CEQA Detailed Results Sheet for the Airbag Cover Assembly Estimate

Both the author and the expert were satisfied that the use of the framework guide the novice well enough in capturing all the necessary information required to develop the airbag cover assembly cost estimate. The tool's result was deemed to be satisfactory, reflecting an estimate of high quality; considering the time limitations under which the case study had to be carried out.

8.3 Aerospace versus Automotive

Comparing the two aerospace case studies to the automotive one the author observed that the process of cost estimating itself does not differ significantly across the two industries. Based on the experience of the author with the collaborating organisations, there are some differences regarding the cost estimating techniques used, but most importantly the purpose, and thus types, of cost estimates developed. Differences in the cost estimating needs are more apparent when OEMs are compared against 1st Tier suppliers, irrespectively of industry. More details are provided in the following Section.

It was observed that aerospace OEMs tend to manufacture a large part of their products in-house, compared to automotive OEMs. During the case studies, a couple of experts commented that there has been a shift of the aerospace industry, as a whole, into out-sourcing work to suppliers, as a more economical way to do business in the long term. The aerospace industry is following on the foot-steps of the automotive industry, in order to reduce costs & risk, and become more flexible and competitive.

8.3.1 Differences in Industries' CE practices

The two industries seem to have many similarities in terms of product complexity and safety & certification requirements. Admittedly, aerospace products abide to higher standards and tend to be slightly more complex in nature. As a result, there is a distinct difference between the two industries in terms of the life-cycle duration of their products; from conception to delivering them into the market. Automotive manufacturers tend to provide the market with new products, or updated variants of existing ones, almost on an annual basis. In contrast, commercial aerospace products have a much longer life-cycle spanning up to 10 years in many cases.

Another difference between the aerospace and automotive industries, on which an expert also commented, was the high level of competition; and as a result the low profit margins in the market. As presented earlier, automotive OEMs tend to outsource the majority of the parts from suppliers, compared to aerospace OEMs which still manufacture in house a large portion of their product. In order to remain competitive automotive OEMs have to 'scrub' their suppliers' quotes and make sure their product is priced in the market, as competitively as possible. In addition, production volumes differ across the two industries, with the automotive industry having to meet much larger volumes compared to the aerospace industry.

As a result of the difference in terms of the expected product development lifecycles between the two industries, the cycle of the cost estimating turn-over varies. Experts commented that within the automotive industry the RFQ lifecycle is 2 to 4 weeks depending on the complexity of the product and work required to complete. This is shorter when compared to typical RFQ lifecycle periods from the aerospace industry, which could well be in the order of 12 weeks time period. That implies that cost estimators are facing tight deadlines in developing their cost estimates; confirming observations found in the literature.

Finally, the author observed that the non-aerospace case study had marginal differences, in terms of some of the CE practices. This observation was based both on informal conversations with the experts from the two domains, as well as the author's gained knowledge on the two industries' CE practices. It was identified that the majority of the cost estimates within the automotive organisation were should-cost estimates, or target-costing exercises regarding their suppliers. This did not seem to occur at such high frequency, within the two aerospace organisations that the author interacted with.

8.3.2 Comparison of Industries in terms of Knowledge and Quality

The involvement of the author in a case study within an automotive environment raised the question of whether the types of cost estimating knowledge differ from the knowledge found within the aerospace domains. As a result, the 'knowledge tree' presented in Chapter 4 (see Figure 4.14) was presented to the expert (during the case study at the automotive organisation) for review. The objective was to identify any similarities and differences between what was developed by the author, based on an aerospace context, against the domain that the automotive cost estimator was familiar with. The expert was asked to think aloud while reviewing the document, and relate the context of the knowledge tree to his line of work. The author recorded the comments and asked questions when further explanations were required.

It was observed that the types of CE knowledge remain similar in both industries. As expected, there are differences in terms of the information underlying some of the types of knowledge, due to differences in the business environment of the industries, products and cost estimating techniques used. However, the automotive expert validating the knowledge tree was content with the presented concepts, captured during the initial interviews that the author carried out. He commented that it provided a satisfactory representation of the knowledge in his domain.

An additional field that the expert felt should be included was the availability of information about the suppliers' rates. The expert suggested that this field should be added under the 'Outsourcing' type of knowledge. Figure 8.22 graphically presents the expert's suggestion (addition is highlighted with dotted lines).

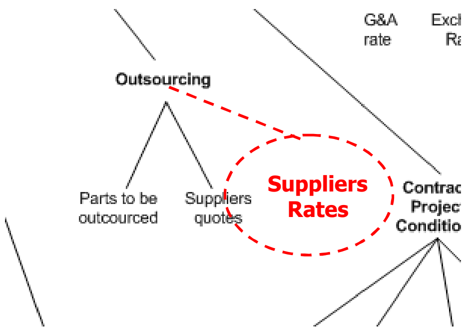


Figure 8.22 – Revision of Knowledge Tree based on the Expert's Comments

The comparison of the results of the two aerospace case studies versus the automotive case study, did not present any significant differences in terms of the knowledge associated with the cost estimation of mechanical hardware products in both industries. The expert from the automotive domain found the types of knowledge to be applicable in his domain, corresponding to the kind of knowledge that a cost estimator usually requires when developing an estimate.

In terms of the characteristics of the quality of cost estimates, the author observed a similar case. No significant differences of opinion were identified between the two industries, based on the feedback received during the three case studies. Experts from both the aerospace and the automotive industry found the characteristics to be representative of what they would expect a good quality estimate to consist of.

8.4 Framework Validation

Validation of the framework was carried out at the end of the two case studies, with the corresponding experts in each company. A de-briefing session was set up at the end of each case study, where the novice presented the work to the expert, and they both went through the whole cost estimate, as well as the completed templates.

The validation process of the results consisted of two distinct stages. In the first stage the expert would validate the cost estimate's results and the various numerical values within the estimate (quantitative approach). In the second stage the expert would verify the knowledge captured and validate the overall framework application in developing the cost estimate (qualitative approach). At the end, the author would elicit the opinion of the experts regarding the methodology's applicability and effectiveness.

8.4.1 Summary of Estimates' Results

As described earlier in this Chapter, upon completion of the exercise, the novice presented his estimate to the expert for analysis. The expert would directly compare the novice's estimate against his, to identify any deviation in the numerical results. Table 8.8 presents a summary of the numerical results for the cost estimates developed during the three case studies.

Table 8.8 – Summary of the Differences Identified in the 3 Case Studies

Case Study	Expert	Novice	Difference (%)	CEQA Result
Case 1 - Fan Cowl Door	$ 17,597.8	$ 17,998.9	2.23 %	81.08 %
Case 2 - Rib Assembly	$ 825.54	$ 815.4	1.23 %	88.38 %
Case 3 - Airbag Cover Assembly	€ 12.03	€ 11.99	0.33%	82.50 %

All three cost estimates that the novice developed were very close to the experts' estimates in terms of their numerical results. A large difference in the results would mean that the novice has probably overlooked something while carrying out his estimate. Large differences as such were absent in the three case studies presented in this thesis. Both the novice and the experts were content with the results and did not identify any areas of concern.

This confidence in the results was further justified by the levels of quality that the estimates exhibited through the application of the CEQA tool. Following the assessment of the three cost estimates with the tool, it was identified that their level of confidence was 81.08% for the Fan Cowl case study, 88.38% for the Rib Assembly case study and 82.5% for the Airbag Cover case study. All three case studies resulted in a score high enough, to indicate that they are of good quality. The application of the tool assisted in identifying the areas of weaknesses in all three case studies, and both the novice and experts were in agreement as to the issues resulting in that score. It should be noted that the tool scores are especially good, considering the small time-frame that the novice had available in order to produce the cost estimates, and also the lack of domain knowledge that the novice had at the start of each case study.

8.4.2 Qualitative Verification

Following the comparison of the numerical results, the expert would then be asked to go through the templates that the novice filled-in, as well as to check the assumptions made in carrying out the cost estimate. The expert would compare the knowledge utilised by the novice against his cost estimate, verify its content, and provide comments and/or suggestions. In summary, in all three case studies the experts did not raise any major concerns with the assumptions and knowledge utilised by the novice in carrying out the cost estimates. Where applicable the experts made some recommendations; however, in overall they were satisfied with the background information supporting the novice's cost estimate. As presented earlier, they were a small number of assumptions made by the novice that the expert corrected, or some missing information from the part of the novice. The details of such shortcomings were presented in the corresponding Sections to the case studies. The templates, and any other supporting information to the cost estimates, are presented in Appendix C.

Following the comparison of the cost estimates and the verification of the knowledge within the templates, the novice held a de-briefing session with the expert, where a number of questions were asked. The purpose of these questions was to obtain the perception of the expert as to the effectiveness of the methodology, as well as capturing any comments that the expert may have had regarding the study. A questionnaire was used during this session. In total, two such sessions were undertaken with two experts, corresponding to case studies 2 & 3. They were the same experts that the novice interacted with throughout the duration of the two case studies. Figure 8.9 presents the questions asked, as well as the experts' responses. A copy of the full questionnaire used to elicit the opinions of the experts regarding the application of the overall framework by the novice, is presented in Appendix A.4.

Table 8.9 – Framework Validation Results

Question	Respondent 1	Respondent 2
Do you agree with the information and knowledge captured within the templates?	Yes, looks like everything has been captured relevant to this kind of estimate.	Discussed during the templates validation.
Do you think the framework has helped the novice to prepare a good estimate?	Cannot be 100% sure. It appears that it may have.	Yes. However it could elaborate more on procedures (process steps) on what to do.
Do you believe the use of the framework reduces the time of interaction with expert (i.e. by using the framework, the novice needs less guidance from expert(s))?	I think it does. It seems like you did not need to rely on us for everything.	Yes, it looks like a novice would need les guidance.
Do you believe the final result (i.e. the estimated cost) is a good measure of how good the novice's estimate is?	It is a good starting point; however one has to look into the assumptions, basis of estimate and supporting documentation in order to get the full story.	Yes; but need also to take into account the data used in coming up with this result.
Do you think the templates and sheets provided within the framework can help a novice know what information he requires in order to prepare a cost estimate?	It could certainly drive the process to an extent.	Yes.
Do you believe the templates (and the use of the framework) have allowed capturing such knowledge; so it can be reviewed by experts at a later stage?	Their main selling-point will be the recording of the knowledge that we use. That would prove usefulness in supporting the inputs within the cost estimate.	They contribute in maintaining a good record of the basis of a cost estimate.
Do you think the use of the framework would contribute towards the formalisation of the cost estimating process?	As mentioned earlier, it would add audit trail. It would also add some structure to the process…so yes. The cost estimate assessment tool would definitely provide some formalisation; we currently do not have any review process available.	Yes. One difficulty is people using slightly different processes. We <*at the expert's organisation*> have a process map; showing how to operate within the business.
Do you believe the learning curve of novice cost estimators could be accelerated, by using the proposed framework?	Could potentially reduce the dependency on more experienced cost estimators.	I believe it could help.

Overall, the experts believed that the use of the framework enables a novice cost estimator to capture all the knowledge associated with the cost estimation of hardware mechanical products. They also expressed that the use of the framework in this case study, resulted in the novice being less dependent on the expert with regards to the development of the cost estimate. They felt that during the case studies, the novice did not need to rely greatly on them. They also agreed that the use of the framework could potentially accelerate the learning curve of novice cost estimators. They identified particular value in the templates and various sheets of the framework, since they provided audit-trail to a cost estimate. In addition, they commented that they believe that the information ,found within the templates, aided the novice in knowing what knowledge he needed, to an extent; thus driving the knowledge elicitation process.

Regarding the question on whether they believe that the use of the framework resulted in developing a good cost estimate, their views were mixed; nevertheless positive. One of the experts commented that he would like to see that the framework provides detailed process steps as to its application, and how it fits with the current processes. Both experts agreed that the use of the framework would contribute towards the formalisation of the current CE processes. They particularly identified the potential in the use of the CEQA tool, as part of their current practices, since they currently do not have any formalised processes for assessing the quality of cost estimates.

Due to the qualitative nature of this study, it is quite difficult to measure the exact impact that the use of the framework had on the overall results. The researcher could only rely on the feedback provided by the experts, and the comparison of the cost estimates, both in a quantitative and qualitative way. In an ideal world, the novice would carry out an estimate without the use of the framework, and then carry out the same estimate using the methodology. However, this kind of approach would severely challenge the reliability of the results, as the novice would have already been familiarised with the domain and task; as a result, being biased. Nevertheless, the author feels that the approach of validating the results, as well as his personal experience in applying the framework, suffices for demonstrating that it indeed helped him in eliciting all the required knowledge for producing a cost estimate of good quality.

8.4.3 Satisfying the Characteristics of a Good Quality Estimate

As presented in Chapter 7, during the development of the KC^2 methodology the identified characteristics of a good quality cost estimate were taken into account. Following the completion of the case studies, the author wanted to explore whether the proposed methodology has satisfied all the, or the majority of the, characteristics of a good quality cost estimate. In particular, focusing on whether the use of the methodology leads to the fulfilment of those characteristics.

Table 8.10 presents the 28 characteristics against how they have been addressed by the KC^2 methodology; along with a justification/explanation. The author used his personal experience with the application of the methodology, which he gained during the case studies, as the basis for carrying out this exercise. Where a characteristic is not applicable in the overall context of assessment (of the framework), a 'N/A' text is provided next to that characteristic.

Table 8.10 – How the KC^2 Methodology Satisfied the Characteristics of a Good Quality Cost Estimate

AS=Assumptions Sheet, ECS=Estimate Cover Sheet, OM=Overall Methodology, SET=Structural Entity Template, MPT=Manufacturing Process Template, RS=Risk Sheet		
Characteristic	**How have they been addressed?**	**Justification**
Documentation of Rules & Assumptions made	AS	All the assumptions made by the Novice are recorded in the Assumptions Sheet
Including a clearly defined scope of work	ECS	Partly captured there
Simple and Clear presentation of results	OM	The use of the provided templates and sheets results into a clear and (and easily understood) presentation of the results
Supplier buys-in the process/model	OM	Partially satisfied. Believed that providing the transparency of the process followed, will help in obtaining the buy-in
Estimate is based on high level of technical detail	SET & MPT	The use of the templates, in conjunction with the probes, could lead in capturing a high level of technical detail
Identification and evaluation of potential risks	RS	The use of this sheet encourages the novice to investigate the existence of any potential risks
Estimate updated for economic period	ECS	The fields present in the Estimate Cover Template encourage the novice to capture Econ. Conditions
Identification of cost drivers (for cost reduction purposes)	AS & SET & MPT	Indirectly; utilising the knowledge captured in the templates and Assumptions Sheet
Estimate is delivered on time	N/A	That would largely depend on external factors
Documentation of data sources	MPT & SET & ECS	The use of the various templates result into the documentation of the critical data utilised by the novice, in the development of a cost estimate
Estimate based on valid quotes of purchased content	MPT	Partially; the template is used to capture any materials and sub-cons quotes
Peer reviewed	OM	Recording all supporting information to the estimate eases the review of the estimate and the supporting documentation by peers

Characteristic	How have they been addressed?	Justification
Assumptions made have been validated by an SME	AS	The purpose of the Assumptions Sheet is to record all assumptions made, so they could be validated by a SME
Credibility and Reliability of data & information sources	MPT & SET & ECS	Indirectly; Fields within the templates, that capture data & information sources, would be checked by an assessor for credibility and reliability
Following a (pre)defined process to generate the estimate	OM	Using the methodology the novice follows a structured pre-defined process in acquiring the knowledge needed
Estimate/model calibrated to company's processes/rates	ECS & MPT & ECS	The use of the templates prompts the novice to identify/find the company's estimating standards and rates
Awareness of the manufacturing quantity and production rate(s)	ECS	The ECS prompts the novice to capture information regarding manufacturing quantity and production rate(s)
Accuracy (specific to the type of estimate/business need)	N/A	Up to the judgement of the estimator; not subject to be driven by the methodology
Estimated cost benchmarked against industry norms	N/A	Not explicitly addressed by the methodology; out of the scope of the methodology's focus
Provision of a Basis of Estimate (BOE) with the estimate	OM	Partially; the completed templates and sheets could form part for a BOE
Use of additional cost estimating techniques for the purposes of cross-check	N/A	Not explicitly addressed by the methodology; out of the scope of the methodology's focus
Estimate, or part of it, can be checked against a known cost	N/A	
Estimate summarises main cost elements	MPT & SET & ECS	Driven by the use of the templates of the methodology
The choice of estimating method is appropriate to the final use of the estimate	N/A	Not explicitly addressed by the methodology; out of the scope of the methodology's focus
Provision of supporting documentation/report	OM	The resulting documentation as a result of using the methodology, could accompany/support the estimate
Shown within the estimate a relationship to schedule	ECS	Information such as delivery dates and important milestones are captured
Have other areas of the business contribute to the estimate	OM	Partially; only in the sense that it can be checked within the various templates, where the information used originated from
Completeness of the WBS/PBS/CBS of the estimate	OM	The use of the composition laddering technique, along with the probes, would lead to a complete PBS/WBS

The proposed methodology addresses the majority of the characteristics which relate to the estimate itself (and its purpose and conditions), documentation, Data & Knowledge utilised and Risk Identification (as per the categories defined in Chapter 6, Section 6.2.3). Where the methodology slightly lacks, is in addressing all the characteristics which have to do with the Estimate Validation. It should be mentioned that nevertheless, the methodology still addresses a number of the characteristics falling within this category.

8.5 Summary and Key Observations

In this Chapter, two additional case studies were presented where the KC^2 methodology was applied by the novice for developing the two cost estimates, respectively. The main purpose was to validate the use of the methodology; whether it actually helps a novice cost estimator to produce a good quality cost estimate, along with all the required knowledge that he may need.

In Section 8.1, the second case study, which took place within an aerospace domain, was presented. The proposed framework was applied in order to elicit all the required knowledge for estimating the cost of a Rib Assembly. A third case study was presented in Section 8.2, which took place within an automotive domain in order to check the applicability of the proposed framework in a non-aerospace domain.

In Section 8.3, the author presented some commentary regarding his observations on the similarities and differences of the aerospace and automotive industry, both in terms of CE practices and knowledge and quality expectations. It was observed that although there were a number of significant differences between the two industries in terms of product development, volumes and market strategies, conceptually, there were not any significant differences regarding the high-level CE processes. Experts from both industries found the types of knowledge to be representative of their domain. Additionally, they found the characteristics of a good quality cost estimate to be representative of their domain and the kind of cost estimates that they typically develop.

Finally in Section 8.4, the author presented a summary of both the quantitative and qualitative validation results for the three case studies. The validation of the framework was effectively carried out in two ways. Firstly, the effectiveness of the framework was investigated through its application on three case studies. A questionnaire was used to elicit the opinions of the experts regarding the framework's effectiveness. Secondly, the researcher had the ability of assessing the quality of the cost estimates development process; and consequently, the resulting quality of the cost estimates. That enabled the researcher to check that a cost estimate was developed with a satisfactory level of quality, which is similar to that of an expert. Finally, the author explored how the various part of the KC^2 methodology satisfied the characteristics of a good quality cost estimate. This analysis was based on the author's experience and familiarisation with the applicability of the methodology in the three case studies.

Some of the key observations of this Chapter are:

- It was demonstrated through the case studies, that the application of the framework by a novice in the cost estimation of hardware mechanical products results into a cost estimate of equal quality to an expert's estimate.
- The methodology was applied in a non-aerospace industrial setting and although the domains significantly differ, it was observed that the cost estimate development process is very similar. The use of the framework was found to be as effective as when it was applied at the aerospace case studies.
- It was identified that the CE domain knowledge does not differ at a high level, with regards to the three organisations studied; thus, validating the types of knowledge as being representative in these domains.
- The framework's effectiveness was validated by two experts. It was observed that its use indeed aids the capture of CE knowledge, as well as aiding novices in producing good quality cost estimates, minimising their dependency on experts. The use of the CEQA tool provided the ability of checking that the resulting cost estimates achieved a high degree of quality; similar to an expert.

In the following Chapter, the key observations and findings of this study are further discussed.

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CHAPTER 9 – DISCUSSION & CONCLUSIONS

In Chapter 7, the development of the proposed framework was presented along with its application on an industrial case study. The framework development was based on observations that emerged from Chapters 4 and 5. The framework consists of two distinct parts: a) a methodology for eliciting CE knowledge, and, b) a proposed method for assessing and quantifying the quality of cost estimates. In Chapter 8, the framework was applied on two further case studies, where the author, assuming the role of a novice cost estimator, developed two cost estimates within the collaborating organisations.

The aim of this Chapter is to summarise the findings of this study and further discuss their implications to the relevant fields. In addition, within this Chapter, the author synthesises all the pieces of work presented so far within this thesis, aiming to provide the reader with a holistic view of this study's findings.

In Section 9.1, the overall thesis and the findings of this research study are discussed. In Section 9.2, a discussion on the quality, generalisability and applicability of the research findings, from a research point of view, is presented. In Section 9.3, the key research contributions are summarised. In Section 9.4, the limitations of the research are presented. In Section 9.5, the author discusses any future work related the subject area. Finally, in Section 9.6, an account of how the research objectives were fulfilled by the findings of this research study, is presented.

9.1 Discussion of Research Findings

In this Section, a discussion of the key observations and research findings is presented. The sequence of the discussion of the findings attempts to reflect the sequence of the work as presented within this thesis.

9.1.1 Literature Review

Through the review of the literature, it was identified that cost estimating is a knowledge intensive process, with knowledge being key towards the development of a cost estimate. Despite that, there are shortcomings within literature regarding the precise knowledge requirements of the cost estimation of hardware mechanical products. In addition, it was observed that when researchers refer to CE knowledge, they often use inter-changeably the concepts of domain CE knowledge and knowledge about the CE practices themselves (such as a cost estimator's skills). The author observed that these two areas of knowledge are conceptually different, and felt that they should be re-defined providing a better distinction between them. Evidence was also presented that the inaccuracies and weaknesses in the development process of cost estimates is attributed to the lack of practical knowledge. Knowledge as such is related to the subject area knowledge, rather than to knowledge regarding the actual CE practices. Novice cost estimators are particularly prone to this problem, since they lack all the necessary experience within a particular subject area. This observation was further justified by the evidence presented regarding the shortcomings of novices, in general, when solving a task. In contrast to experts, novices tend to follow rules and guidelines since they lack the experience and intuitive grasp of situations.

It was identified that there is a lack of an in-depth study regarding the perception of quality of cost estimates. In particular, there is a lack of definition with regards to the inherent ingredients of a cost estimate, which fulfilment would result in the realisation of good quality. It was observed within the literature that reviewing cost estimates is a highly subjective process, the result of which is often not quantifiably measured. Consequently, it may prove difficult to express how good, or bad, a cost estimate is. An additional shortcoming of the current CE practices is the lack of a standard, based on which an estimate's quality could be benchmarked against, following the review process of a cost estimate.

The development of cost estimates is based on a large amount of knowledge, often accumulated by cost estimators through years of experience in a particular domain. Since novice cost estimators lack such experience, when they produce an estimate they depend on experienced cost estimators or other Subject Matter Experts (SMEs) for obtaining the required estimate inputs. In addition, novice estimators lack the necessary knowledge enabling them to make assumptions, logical derivations or in general to apply their judgement as experts would. Due to that inexperience, novice cost estimators often find it difficult to: a) know what they need in terms of knowledge, and, b) how to acquire such knowledge. The process of acquiring CE knowledge, necessary for developing a cost estimate, is currently unstructured and does not rely on the use of any formal techniques or methodologies. The review of the literature revealed that there is a lack of available methodologies that novice cost estimators could use to elicit cost estimating knowledge. Following the review of the literature, it was identified that available methodologies, from other discipline areas, could not be directly applied in a CE domain such as the one in the context of this study. The reasons were provided in Chapter 2. Nevertheless, the author identified that there is potential in borrowing key concepts from such methodologies, and integrating them with available KEL techniques, in developing a KEL methodology which would be tailored to the current needs of novice cost estimators.

In summary, it was identified that both the assessment of cost estimates and the elicitation of knowledge during the development of a cost estimate, involve a high degree of subjectivity. In addition, it was observed that there is a lack of formalisation in both processes. The successful undertaking of these processes relies on the experience, skills, knowledge and the judgement of the cost estimators. There is a lack of formal methods and techniques, tailored to the cost estimating needs, which practitioners can apply in order to add more credibility to their work; by ensuring that there is transparency and an auditable, structured process. This observation was further confirmed by some of the findings presented in Chapters 4 and 5.

9.1.2 Strengths of the Research Methodology

One of the main strengths of the research methodology was the variety in the data collection methods utilised by the author, in ensuring that the weakness of a particular method does not result in a distorted representation of the results. A further strength of the research methodology was the fact that the researcher was actively involved in the selection of the particular case studies. The selection process was not left solely to the experts; the author made sure that these case studies were in accordance with both the research context and requirements of this study. A case study approach was selected as the most suitable research strategy, for the reasons presented in Chapter 3. In order to minimise bias throughout the study, the author carefully designed the research approach in carrying out the case studies.

A presented in Chapter 3, qualitative research is prone to bias and subjective interpretation by the researcher. Since the author assumed the role of the novice cost estimator during the case studies, a potential source of bias is that he may have been influenced by the fact of being aware of what the research problem was. A measure taken to minimise this bias was to feed-back to experts the results at various points in time, as a sanity check, as well as the use of multiple data collection techniques.

9.1.3 Cost Estimating Knowledge

The use of the IDEF0 models proved invaluable in constructing a view of the current cost estimating processes. It allowed the author to capture in a graphical way the current processes, following the semi-structured interviews that took place with experienced cost estimators. The outcome of the interviews was a structured model of the CE process, with respect to the organisations studied, which in turn highlighted the various interactions within the overall process, as well as the knowledge requirements surrounding the process.

In addition, the author proposed a differentiation with regards to the knowledge associated with cost estimating. The proposition suggests that CE knowledge consists of: a) Cost estimating domain knowledge, and, b) Knowledge related to the cost estimating practices. This study focused on the former, as it identified that CE domain knowledge is of prime importance, and consequently, constitutes the difference in terms of knowledge between an expert and a novice cost estimator in a particular domain.

The analysis of the resulting IDEF0 models, the analysis of a number of cost estimates, as well as the results from the interviews with experienced cost estimators led to the identification of the CE knowledge requirements. In particular, 10 main types of cost estimating knowledge were identified, which are believed to represent the high level knowledge needs of cost estimators. The resulting CE knowledge representation was validated by experts, and was found to be applicable in at least 2 different industries; the aerospace and automotive industry. The hierarchical representation of the main types of knowledge, along with their lower level classification of the information types, is a novel insight into how cost estimating domain knowledge is perceived and utilised. It provides a view of the CE knowledge in general, rather than focusing on a particular product type and/or organisation.

The following step in the analysis of the CE knowledge included the identification of the characteristics of these types of knowledge. The types of knowledge were analysed in terms of their nature. As a result, it was identified that their nature varies, and not all the types exhibit the same attributes. The results of this finding were implemented during the selection of the available KEL techniques, suitable for eliciting these particular knowledge types (as part of the proposed methodology). Finally, some typical forms and sources of these types of knowledge were also identified.

9.1.4 Assessing & Quantifying the Quality of Cost Estimates

A survey was carried out across a number of cost practitioners, with the aim of identifying the inherent characteristics of a good quality cost estimate (work presented in Chapter 5). Based on the survey study results, 28 characteristics were identified, believed to contribute towards the attainment of quality of a cost estimate. The findings of this study are novel in the sense of identifying the ingredients of a good quality cost estimate; setting a standard of what consequently a good cost estimate should conform to. The fulfilment of these inherent characteristics during the CE development process is going to result in producing a good quality cost estimate. A quantitative method was proposed which could be used for assessing the quality of cost estimates, based on the rating of these characteristics. The author assumed that each characteristic does not contribute the same amount towards the estimate quality.

Consequently, an online follow-up questionnaire consisting of semantic differential scales was forwarded to the survey participants, in order to elicit their perception regarding the relative contribution of each characteristic towards the overall estimate quality. The results of the follow-up session indicated that indeed the assumption appears to stand true, confirming that each characteristic does not contribute the same amount towards the estimate quality. As a result, the relative importance of each characteristic towards the overall estimate quality was quantified.

Due to the quantitative nature of the results, the researcher was able to analyse the results using a statistical software package. The statistical analysis of the sub-groups did not exhibit any major differences in terms of opinion. Thus, the proposed method could be applied in the assessment of cost estimates, within a variety of industries, sectors and estimate types. This suggestion is further supported by the fact that the identification of the characteristics and their relative importance was based on a sample of cost estimators representing various industries, sectors and experience levels.

A software tool was developed, in order to find out whether the proposed method provides results close to the subjective perception of highly experienced cost estimators. The prototype tool was used for assessing and quantifying the quality of 9 cost estimates. Cost estimators initially provided their subjective judgement regarding how good they believed their estimate to be. They proceeded in rating their cost estimate, based on the characteristics found within the tool. The tool's indicated results were directly compared against the users' perceptions. The results suggested that the proposed mathematical representation, for quantifying the quality of cost estimates based on the 28 characteristics, is representative of experts' subjective perceptions.

As it was identified in Chapter 2, the review process of cost estimates is currently highly subjective; with a distinct lack of any formal processes or tools to support this process. The CEQA tool is a novel proposition for quantifying the quality of cost estimates, based on the rating of the 28 characteristics. The application of the tool within an industrial environment is going to improve the estimate review process, by minimising the subjectivity that currently surrounds this process. The tool could be incorporated within the current CE practices in industry, for assessing and quantifying the quality of cost estimates upon their completion. In addition, it will aid cost estimators with highlighting the areas of weaknesses in their cost estimates.

9.1.5 KC^2 Methodology Development

The review of the literature led to the realisation that cost estimating is a knowledge intensive process, yet there is a lack of structured methods for eliciting the required knowledge. The elicitation of the CE knowledge becomes a bottleneck in the cost estimating process, especially in the case of novice cost estimators; since they lack the necessary expertise and background in developing an estimate in a domain which may be unfamiliar to them. Novice cost estimators require rules and guidance with respect to carrying out a task, and they will often face difficulties, and seek help from experts. As a result, the need for developing a KEL methodology was identified, which would guide novice cost estimators through the process of capturing all the necessary knowledge for developing a cost estimate.

The development of the KC^2 methodology was presented in Chapter 7, based on a number of criteria, as well as a number of findings from Chapters 4 and 5. Structured templates were developed, customised to the CE knowledge needs. Their utilisation will guide novice cost estimators in capturing all the necessary knowledge. The basis of the fields residing within the templates was the CE knowledge classification, which was presented in Chapter 4. A list of generic questions was produced with the purpose of accompanying the templates of the methodology. Finally, available KEL techniques were utilised within the overall methodology, such as the composition laddering technique that could be used for identifying the breakdown structure of a product into its lower level physical parts. The KC^2 methodology was applied in industry through the use of case studies, as part of an overall framework. The resulting findings are presented in the following Section.

9.1.6 Framework Application

The KC^2 methodology and the CEQA tool were merged to form an overall framework. The framework was applied on three industrial case studies; two of which took place within an aerospace domain and the third within an automotive. During each case study the author, being a novice in these respective domains, was required to develop a cost estimate using the same tools and resources that an expert had used. The expert had already developed a cost estimate for the same product before the exercise took place. As a result, the author had a point of reference for comparing the end result of his cost estimate against the expert's work. At the end of each exercise the expert would review and verify all the knowledge utilised by the novice throughout the development of his cost estimate.

The proposed framework was utilised in order to produce the cost estimates during each case study. In particular, the application of the methodology enabled the author to elicit cost estimating knowledge essential in developing his cost estimate. The use of the methodology's structured templates guided the novice with regards to the knowledge requirements for developing the cost estimate. As a novice, he utilised the various parts of the methodology for interacting with the expert, and with other SMEs. The use of the assumptions sheet enabled him to capture knowledge relevant to the cost estimate, following the interaction with the expert. The templates of the methodology resulted in an extensive audit trail, with regards to the inputs of the cost estimate and the knowledge utilised.

Upon completion of each cost estimate, the novice, in collaboration with the expert, applied the CEQA tool for assessing and quantifying the quality of his estimate. For all three case studies, the assessment exercise resulted in levels of quality that were high. The tool's indicative results showed that the novice, following the use of the framework and knowledge acquired from the expert, could achieve a high level of quality in his cost estimate; similar to that of an expert. The areas of weaknesses identified by the CEQA tool were found to be representative of the novice's cost estimate.

An additional method for assessing the novice's cost estimate was a review process by the expert, during a de-brief session. The expert focused on two main areas: a) compare the numerical results for identifying similarities and/or differences, and, b) qualitatively compare his estimate against the novice's in terms of data utilised, assumptions made, rationale and knowledge utilised. These comparison exercises did exhibit a few differences between the two cost estimates; nevertheless, nothing of significant nature. The novice appeared to have captured most of the knowledge associated with each particular cost estimate. The expert verified all the knowledge utilised by the novice, and gave suggestions where necessary.

At the end of each case study experts were presented with a questionnaire for capturing their views regarding the effectiveness of the framework. In summary, the experts believed that the framework did help the novice in developing the estimate and acquiring all the essential knowledge. They identified that there is benefit in using the methodology in order to reduce the dependency of novices upon experts, and reduce the resources that novices require for developing a cost estimate in industry. Their views were that the application of the framework could contribute towards the formalisation of their current processes. They felt that the use of a structured process in these subjective areas (of estimate review & knowledge elicitation) would help them to improve the quality of their overall CE process; and as a consequence, the quality of their cost estimates.

9.2 Quality, Generalisability & Implications of Findings

In this Section, a number of issues related to the quality and generalisability of the research results are discussed. In addition, the implications, and business impact, of applying the research findings in industry, are discussed.

9.2.1 Quality of Research Findings

As far as the results of the case studies are concerned, the author took the necessary steps in ensuring that the overall process and the analysis of the results were carried out in a thorough manner. Although there was a limitation as to the time available to the researcher to carry out each case study, pro-active measures were taken, such as selecting cases which would be manageable within the available timeframe, and consultation with the experts in advance of the case studies taking place, so everything would be in place during each case study activity.

The results of each case study were validated by experts in each domain, both in a qualitative and quantitative way. The qualitative approach involved the verification of the content of each template and sheet that the novice completed, as well as a qualitative comparison of the overall cost estimate produced by the novice, against the expert’s estimate. In addition, a questionnaire was used to elicit the opinions of the experts with regards to the framework effectiveness. Quantitative validation took place by directly comparing the numerical results of the novice’s cost estimate, against to the results of the expert’s estimate. Comparison of the numerical results is not the most appropriate way of drawing any concrete conclusions; nevertheless it provides an additional means of comparing the work of the novice and expert as a sanity check that their estimates do not greatly differ. In addition, the novice had the ability to check the quality of the resulting cost estimate through the use of the CEQA tool. Its application provided an additional means of assessing that indeed the use of the overall framework had resulted in producing a good quality cost estimate.

Throughout the course of this study, the author aimed at maintaining a high degree of reliability into the methods and practices used in reaching this study’s findings. This was achieved through the use of semi-structured questionnaires, along with the use of other data collection methods and the development of a formal research strategy. Triangulation of data and methods was implemented, whenever possible, as well as the use of difference data sources throughout the case studies.

9.2.2 Generalisability of Research Findings

The proposed framework, and in particular the knowledge elicitation methodology, was demonstrated to be applicable in the cost estimation of complex mechanical hardware products within the aerospace and automotive industries. The framework could be potentially applied to other domains with similar results; however, further case studies in other industries were not undertaken in order to come up with the evidence for substantiating such a claim. The author believes that the framework is not limited to a particular industry, but rather to types of estimates produced (and consequently of products being estimated). In the future, additional case studies may be required in order to test these beliefs. Until this materialises, the boundaries for the applicability of the proposed framework are on the aerospace and automotive industry, involving the cost estimation of mechanical hardware products.

A part of the overall framework, and its corresponding findings, are more generally applicable compared to the KC^2 methodology itself. The research findings regarding the quality of cost estimates are not bounded to a particular industry, or product for that matter, due to two reasons. Firstly, the sample of the survey participants, for identifying the characteristics of a good quality estimate, consisted of cost estimators coming from various industries, dealing with different types of estimates and utilising various cost estimating techniques. Secondly, the validation of the proposed method was carried out by applying the tool in 9 test-cases, which varied quite a lot in terms of applicable industry, product nature, as well as type of estimate. The subsequent findings suggest that the method, implemented through the use of the CEQA tool, did not exhibit any limitations in terms of its applicability to different domains.

9.2.3 Applicability of Findings & Business Impact Analysis

In this Section, the applicability of the findings in industry and the potential business impact as a result of their implementation is discussed. In particular, the adoption of the framework by industry, incorporated within their current CE processes, is discussed. Since the framework consists of two distinct parts, the business impact of the implementation of these parts is separately addressed.

The KC^2 methodology could be easily implemented within any industrial setting, which fits the boundaries of the research context. The methodology could help novice cost estimators with eliciting the knowledge required for developing cost estimates. It would provide them with the means of guiding them with respect to the knowledge required for developing an estimate, and more importantly, provide them guidance about how to elicit this knowledge. As a result, each cost estimate developed with the use of the methodology, is going to have a comprehensive record of the knowledge utilised in producing that estimate. Additionally, novice cost estimators will have a means of storing the knowledge gained during the development of an estimate, which could be re-used at a future point in time. The various templates could be even stored in electronic form; thus making it easier to link them, as well as automating the process of producing cost estimate reports.

Cost estimators could integrate this methodology within their current processes. In Figure 4.15, the way in which the methodology could be applied in order to improve the current CE process is presented. In particular, the methodology would be found invaluable in instances where a novice cost estimator is joining an organisation. Its use could potentially accelerate the learning curve of novice estimators, saving time, resources as well as utilisation of busy experts. Minor adjustments may be required to some of the templates in order to customise them and make them more relevant to a particular organisation's cost estimating processes. In terms of training needs, three to five hours will be enough for familiarising a cost estimator with the methodology. A workshop involving many cost estimators would reduce the overall impact on the business. No special resources are required in order to implement the methodology.

Similarly, the CEQA tool could be incorporated to the current CE processes of an organisation, in order to complement the estimate review process. The tool could be used upon the completion of a cost estimate for assessing and quantifying its quality, and consequently identify the confidence that should be placed by decision makers upon that particular estimate. The author presented in Figure 4.15 where exactly this activity takes place during the CE process. The potential use of the CEQA tool is not restricted to novice cost estimators only; experienced cost estimators could also use it, as well as professionals of other background such as project managers, proposal managers, and so on. The potential benefits of implementing the tool within the current processes would be an increase of confidence with regards to the cost estimating practice, since cost estimators will have a means of objectively communicating to others how confident they are of their estimates. In addition, cost estimators could improve the quality of their estimates, as they will have a structured process of identifying areas of weaknesses in their work.

Implementation of the CEQA tool within the current processes, in industry, should not require any major additional work. The overall impact of such implementation is envisaged to be low, since it does not require any major resources or financial backing. A training session of one to two hours in duration would suffice for making sure that cost estimators are familiarised with using the tool. The main impact will be cultural, since both cost estimators and decision makers would have to be convinced that the tool and its results are reliable and credible. Its implementation within an organisation would require some initial 'test period' where the tool's result could be benchmarked against the subjective perception of the individuals currently assessing cost estimates.

9.3 Key Research Contributions

The outcome of this research was an increased understanding regarding the knowledge associated with developing cost estimates, and how this knowledge could be elicited and captured following a structured methodology. In addition, this research contributed towards a richer view of what is quality in CE and what are the inherent characteristics contributing to a good quality cost estimate. As a result, a novel method was developed that can be used to assess and quantify the quality of cost estimates. This method was coupled with a KEL methodology tailored to CE knowledge, to form an overall framework that could be used to improve the quality of cost estimates. In summary, the findings of this research contributed towards the formalisation of the cost estimating practice, which is currently plagued by the subjectivity and informality involved in some of its processes (such as estimate reviewing and knowledge capture).

The key research contributions of this study are summarised into the following key points:

- This research identified through literature that a number of the current cost estimating processes involve a high degree of subjectivity; as a consequence the overall discipline of cost estimating is being described as 'part art, part science'. In particular, it was identified that there is a lack of formal methods for eliciting CE knowledge and a lack of an in-depth understanding regarding the quality of cost estimates.
- This research identified that the perceived quality of a cost estimate depends upon the fulfilment of 28 characteristics, related to the overall CE process. The relative importance of each characteristic towards the overall estimate quality was identified following a survey study.
- As a result of this research's findings, a novel method was proposed that could be used to assess and quantify the quality of cost estimates based on the rating of the 28 inherent characteristics. The method was implemented in the form of a prototype tool (CEQA), and its application on a number of test-cases demonstrated that its results are very close to the subjective perception of experienced cost estimators.
- This research has also resulted in the development of a structured KEL methodology that can be used by novice cost estimators in eliciting the knowledge associated with producing a cost estimate for complex mechanical hardware products. The KEL methodology and the CEQA tool were integrated into a framework, which could be applied by cost estimators in order to improve the quality of their cost estimates.

In the following Section, the limitations of this study are presented.

9.4 Research Limitations

In this Section, the limitations of the research methodology are presented, as well as the overall research limitations in respect to the research findings. Due to the qualitative nature of this study, there a number of areas of concern with regards to the limitations associated with carrying out a qualitative inquiry; which were presented in Chapter 3. One of the main issues has to do with the replicability of the results, compared to quantitative research where the replicability could be established in an easier fashion.

As presented in Chapter 3, prolonged involvement could result in researcher bias resulting in misrepresentation or skew-ness of the results. In this study, the duration of each case study did not involve the author spending lengthy amounts of time at the respective organisations. Although the author aimed at prolonging his involvement within the research setting, in some cases the time spent at undertaking a case study was quite limited; due to time limitations, resources and experts availability. In order to counteract the potential effects of the limited time periods, the researcher undertook some actions in ensuring that the case studies were carried out to a satisfactory degree. Actions as such involved: a) careful pro-active planning of the case study, by collaborating with the experts in making sure that everything is in place, and that there is a common understanding of what is required, b) being involved in the selection of the cases, making sure that the effort required in producing the cost estimates is proportional to the available time, and, c) following-up with the experts on any outstanding matters after each case study was completed.

With respect to the validation of the developed framework, the ideal approach would be for the researcher to produce a cost estimate without the use of the framework; and then produce again a cost estimate for the same product by utilising the framework. This would provide a clear comparison as to the impact that the framework had on the resulting quality of the estimate, and would highlight and strengths or weaknesses that the application of the framework imparts on the quality of the cost estimating process. However, it became apparent to the author that this approach was not realistic for carrying out the three case studies, since it would potentially introduce bias to the results. The reason is that the researcher would have already been familiar with the domain and problem, and would have already formed some ideas during producing the first cost estimate. As a result, when repeating the process with the use of the framework, the results would not be fully representative, as the author would not be 'truly' novice by that point in time.

Finally, a limitation was identified in the analysis of the initial survey data. During the first stage of the survey, the filtering and sorting of the survey responses was undertaken by the author qualitatively, due to the peculiar nature of the data. This process may be prone to subjective interpretation. To minimise any potential bias the author made sure that the results of the analysis were presented back to the survey participants for comments and validation.

9.5 Future Work

In this Section, a number of potential areas of future work derived from this study's research findings are presented. The next step in complementing the proposed methodology could be some further work on providing some formal representation schemas in representing the knowledge captured. Representing this knowledge in a formal way will result in easing the process of its re-use. Ideas could be drawn in from the available modelling frameworks found in the engineering design domain in order to expand the context and applicability of the developed methodology. Combining the KEL methodology with a modelling framework as such, could result in the automation of sorting and representing cost estimating knowledge, from the templates to a more formal medium. The development of an ontology could contribute in facilitating this approach.

Future work needs to be undertaken in order to understand how the proposed framework could be applied on developing cost estimates with alternative cost estimating techniques. Within this study the development of cost estimates, following the traditional, generative-based, CE approach was presented; mainly with the utilisation of the detailed bottom-up technique. Further research would need to be carried out in order to test the applicability of the framework for developing cost estimates utilising other CE techniques (such as parametric, analogy, feature-based). A question raised is whether the CE knowledge needs, associated with the use of these alternative techniques, differ. Further research is required in order to identify what are the similarities or differences in the nature of the CE knowledge, and what are the implications with respect to the elicitation of that knowledge.

The CEQA tool was a prototype tool used for testing the proposed method. The author can envisage its further development, into a fully functional software tool that could have the ability to store estimate assessments, and make quick comparisons to past reference points. Thus, cost estimators would be able to keep track of the progress of the development of a cost estimate throughout the life of a project. This would potentially prove helpful in improving their estimating skills, through the auditability and lessons learned which could be stored within the tool. Capturing snapshots of an estimate's quality, during its development, was not demonstrated in the case studies presented in this thesis, due to time constraints that the researcher was facing. However, any obvious limitations in being able to implement the tool in such manner were not identified. This vision was also shared by one of the cost estimators who took part in the tool validation exercise.

It was assumed that the weights, applied in the determination of the perceived quality of cost estimates, did not vary across the test-cases. This was due to the evidence originating from the results of the statistical analysis, which did not exhibit many statistically significant differences. A larger sample of responses would help in further confirming whether this assumption stands true for all types of estimates, or whether the values of these weights could potentially vary depending on individual circumstances. In addition, although the findings indicate that the use of the CEQA tool leads to results very close to an expert's subjective perception, further test cases would be required in order to make sure that the proposed method is highly reliable. Increasing the credibility in the use of the CEQA tool, could potentially result in the tool becoming an industry best practice; and form an integral part of the cost estimating discipline within industry.

9.6 Conclusions

In this Section, a synopsis of the study presented in this thesis is provided. In summary, this research study has achieved the aim & objectives as defined in Chapter 3.

The first objective was to identify through the review of the literature the key issues regarding the current CE practices; and explore their shortcomings. In particular to explore what are the problems in the current cost estimating practices, in terms of the knowledge associated in developing a cost estimate and the quality of the CE development process. The key issues which emerged from the review of the literature, are:

- Although cost estimating is a knowledge intensive process, there is a lack of focus on the knowledge requirements for cost estimating, especially in the case of complex mechanical hardware products; where knowledge and skills are often used inter-changeably in literature.
- Inaccuracies to cost estimates are often the result of the lack of practical knowledge. Novice cost estimators are particularly prone to this phenomenon.
- Novices tend to follow rules and guidelines, since they lack the experience and intuitive grasp of situations that an expert possesses.

- There is a lack of available structured methodologies for eliciting cost estimating knowledge.
- There is a lack of understanding regarding the perceived quality of cost estimates.
- The review of cost estimates is currently a highly subjective process, relying on the subjective judgement of the reviewer.
- The end result of the estimate review process is not quantified; thus, being difficult to put the quality of a particular cost estimate into perspective.

The second objective was to improve the understanding about the knowledge utilised by cost estimators in developing cost estimates for complex mechanical hardware products; and propose a systematic approach for reducing the subjectivity in the way that knowledge is currently captured. It was identified that:

- Some of the current CE processes, such as knowledge elicitation and estimate reviewing, involve a high degree of subjectivity. This was identified by capturing the current CE process in a formal model, through a series of interviews with experts.
- CE knowledge could be further decomposed, based on its nature. The author suggested that CE knowledge consists of: a) CE domain knowledge, and, b) knowledge regarding the CE practices (Section 4.2.1).
- CE domain knowledge cannot be gained only through training; it is largely constructed based on the accumulation of experience in a particular domain.
- The CE domain knowledge for mechanical hardware products consists of 10 main knowledge types. A hierarchical representation of these types was presented in Section 4.3.3. This representation was validated by three experts from the aerospace and automotive industries.
- CE knowledge varies, both in nature and in terms of discipline areas involvement (Section 4.4.1).
- Cost estimators do not make use of any formal methodologies for eliciting the required knowledge for their estimates; the process is currently 'ad-hoc'.
- There is a lack of any formal methods for reviewing cost estimates within industry. In fact, none of the organisations studied had any formal review activity as part of their overall CE process.
- The shortcomings in these particular CE activities are believed to negatively influence the quality of the resulting cost estimates. The author proposed a number of improvements to the current practices (Section 4.3.5).

The third objective was to understand the perception of quality in cost estimates, within the industry. A survey was carried out with a number of experienced cost practitioners in order to develop a better understanding regarding the factors contributing to the quality of cost estimates. It was identified that:

- There are 28 inherent characteristics that contribute towards the achievement of quality in a cost estimate (Section 5.2.3).
- The make-up of these inherent characteristics was found to be related to the cost estimating development process.
- A number of the survey respondents felt that there is a large amount of subjectivity currently involved in the process of reviewing cost estimates.
- The relative importance of each characteristic towards the overall estimate quality varies. As a result, the respective weight of each characteristic was identified (Section 5.3.3).
- Following the use of statistical analysis, the perception of cost estimators within the sample was found to be quite similar; regardless of industry, sector, cost estimating technique employed, position and/or experience.

The fourth objective was to minimise the subjectivity involved in the review process of cost estimates, by developing a structured method for assessing and quantifying their quality. The author achieved that, by:

- Proposing a method for assessing and quantifying the quality of cost estimates, based on the rating of the 28 characteristics (Section 5.3.1).
- Developing a software tool (CEQA), in order to interact with cost estimators for the purposes of testing the accuracy of the proposed method (Section 6.2).
- Carrying out 9 test-cases, where cost estimators applied the tool in assessing the quality of their cost estimates. It was identified that the tool's results demonstrated a high correlation against the subjective judgement of these cost estimators (Section 6.3.3).
- Identifying that the cost estimators' perception is slightly higher than the tool's results; exhibiting a level of over-confidence with regards to the quality of the process followed in developing a cost estimate.
- Validating the applicability of the CEQA tool with these experts at the end of each test-case, through the use of a questionnaire (Section 6.3.5).
- Identifying that the proposed method appears to be generic in use, due to the diversity of the test-cases & cost estimators' background, as well as the positive results obtained.

The fifth objective was to increase the formalisation of the current CE processes, by providing novice cost estimators with a framework that they could utilise for improving the quality of their cost estimates. To achieve this objective, the author:

- Incorporated the KC^2 methodology and the CEQA tool into an overall framework. Applied the framework on three case studies, and validated their results with the collaborating sponsors, for estimating the cost of mechanical hardware products.

- As a novice cost estimator, captured the CE domain knowledge necessary for developing the cost estimates to a high degree of quality, through the application of the KC^2 methodology.
- Demonstrated that the use of the framework by a novice cost estimator, in conjunction with knowledge acquired from an expert, could result in producing a cost estimate which level of quality is similar to an expert's.
- Identified that the use of the framework could increase the formalisation of the current CE practices, based on feedback received from experts.
- Demonstrated the effectiveness of the framework through the development of case studies within two different industries; the aerospace and automotive industries.

Based on this study's findings, the author believes that the implementation of the findings of this research within industry will contribute towards the formalisation of the CE practice. Formalisation as such could potentially lead to an increased confidence and credibility of cost estimates within organisations; and how the role and 'value-add' of cost estimating is perceived.

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APPENDIX A – QUESTIONNAIRES

All the questionnaires used throughout the course of this study, are presented in this Appendix. The questionnaire used for interviewing cost practitioners in understanding the cost estimating processes within their organisation, as well as the knowledge requirements, is presented in Appendix A.1.

A.1 CE Process and Knowledge Requirements Questionnaire

Questionnaire

Disclaimer: The content of this questionnaire is going to be used by the research student for the purposes of his research only. The anonymity of the respondent will be maintained at all times

A) Respondent & Company Details

1. How many employees your company has?

2. Could you describe to me the main products that your company produces?

3. Are specific sites responsible for specific range of products? If so, which site has the responsibility of what products?

4. What is your job role in the company?

5. For how many years have you been doing this job?

6. Is cost estimating your main role or an additional task as part of your work?

B) Cost Estimating Practice

1. What type of estimates are you required to generate, which cost estimating techniques you use and for what kind of products?

2. Could you briefly list the steps that you follow during the task of generating an estimate?

3. During those steps what information you generally need to obtain and what knowledge is required by your part?

4. Are there any standard practices followed by cost estimators in your organisation for acquiring and archiving the knowledge used for producing an estimate?

D) Knowledge required for producing a cost estimate

1. While producing an estimate for a specific product what knowledge you need to have as an estimator, in order to complete the task?

2. In cases where you do not have knowledge for a certain issue relating the product, how do you acquire it? Are there any specific techniques you would use?

3. What problems you generally have in acquiring the knowledge needed (i.e. not knowing who to contact, experts are hard to find or busy, not sure what you are after)?

4. When particular information is impossible to obtain do you make assumptions based on your judgement? In a case like that do you use the judgement of other cost estimators to support an assumption made?

5. Are the assumptions captured in an explicit format (either on the estimate or on a separate document)?

6. In the case where a novice cost estimator produces an estimate, and s/he is not able to make accurate assumptions, what do you think s/he could do in order to compensate for that lack of experience?

A.2 Quality of a Cost Estimate (Part 1) Questionnaire

What is a good quality estimate?

Introduction: The purpose of this questionnaire is to identify the crucial characteristics that define a good quality estimate. This work is part of a PhD study, undertaken at Cranfield University, which focuses on the identification of knowledge required in cost estimating and methods to capture such knowledge. We value your opinion as an expert, thus we would like you to share your views on the subject.

Instructions: This questionnaire is divided into two sections. Please complete this questionnaire, section by section, in the sequence that is provided within here. It is important that you fully complete each section before moving into the next one. When you have completed the questionnaire, you could submit it via **email or fax** (contact details are provided at the bottom of this page).

Disclaimer: The answers provided will be used for this research's purposes only. The answers will be treated anonymously at all times. The results of this survey will be sent to all the correspondents that took part in it, via electronic mail.

Contact Details:
Evaggelos Lavdas
Cranfield University, UK
Tel: ++ 44 (0) 1234 754193
Fax: ++ 44 (0) 1234 750852
E.Lavdas@cranfield.ac.uk

SECTION 1 - Personal Details:

Name:	
Company:	
Position:	
Type of Industry: (eg. Aerospace, Automotive etc)	
Cost Estimating experience (years):	
Email address:	

(Please note that the results of this survey will be forwarded into the email address that you provide in the field above)

Telephone Number:	

<u>SECTION 2 - Questions</u>:

(Please try to summarise your answers in around 50 to 70 words per question; wherever applicable)

2.1 What types of estimates do you usually undertake, as part of your every job (eg. bid proposal, budget, rough order of magnitude, should cost, etc)?

2.2 Which cost estimating technique(s) are you using to carry out those estimates (eg. analogy, parametric or detailed)?

2.3 When would you consider a cost estimate to be of good quality? If possible, please list the characteristics that you believe a good cost estimate should have.

2.4 In your opinion, how could one check the quality of a cost estimate? Are there any metrics that could be used and what should one look for?

2.5 How would you typically be required to justify an estimate, which you prepared, to your manager?

2.6 Finally, when would you consider a cost estimate to be a bad estimate? What are the characteristics of a bad estimate?

Finally, you could use the space below to add any comments you may have:

A.3 Quality of a Cost Estimate (Part 2) online Questionnaire

This Section provides screenshots of the online questionnaire which was used for eliciting the perceptions of the respondents towards the identified characteristics of a good quality cost estimate. After a short description regarding the purpose of the survey, and a set of instructions for the participants to follow, the participants would be directed to the first part of the questionnaire. The purpose of this page was to find out which CE techniques cost estimators tend to use in their daily job. The first part of the questionnaire is presented in Figure A.1.

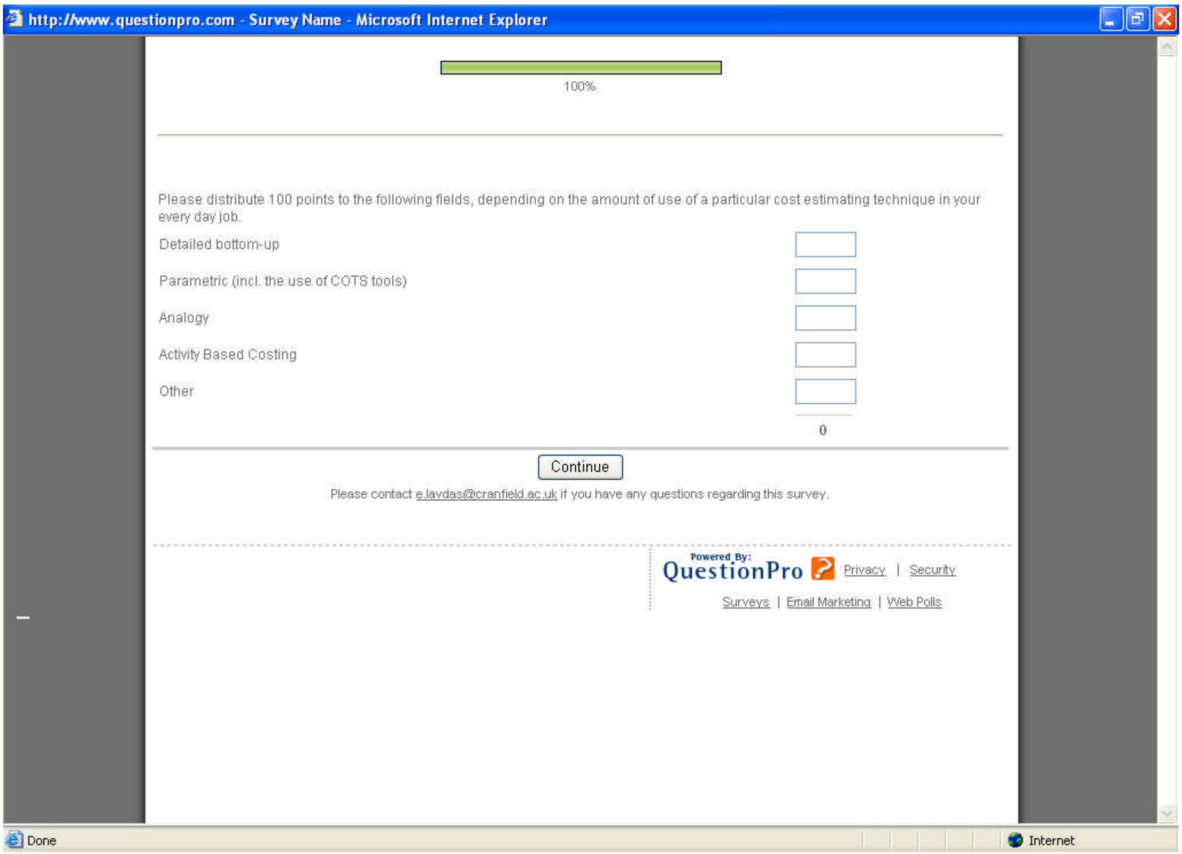


Figure A.1 – First Part of Online Questionnaire

Upon completion of the first part of the questionnaire, the survey participants would be directed to the second part of the online questionnaire. The purpose of this part was to find out how cost estimators feel regarding the importance of each of the characteristics against the overall estimate quality. The second part of the questionnaire is presented in Figures A.2, A.3, A.4 and A.5.

Figure A.2 – Second Part of Online Questionnaire (Page 1)

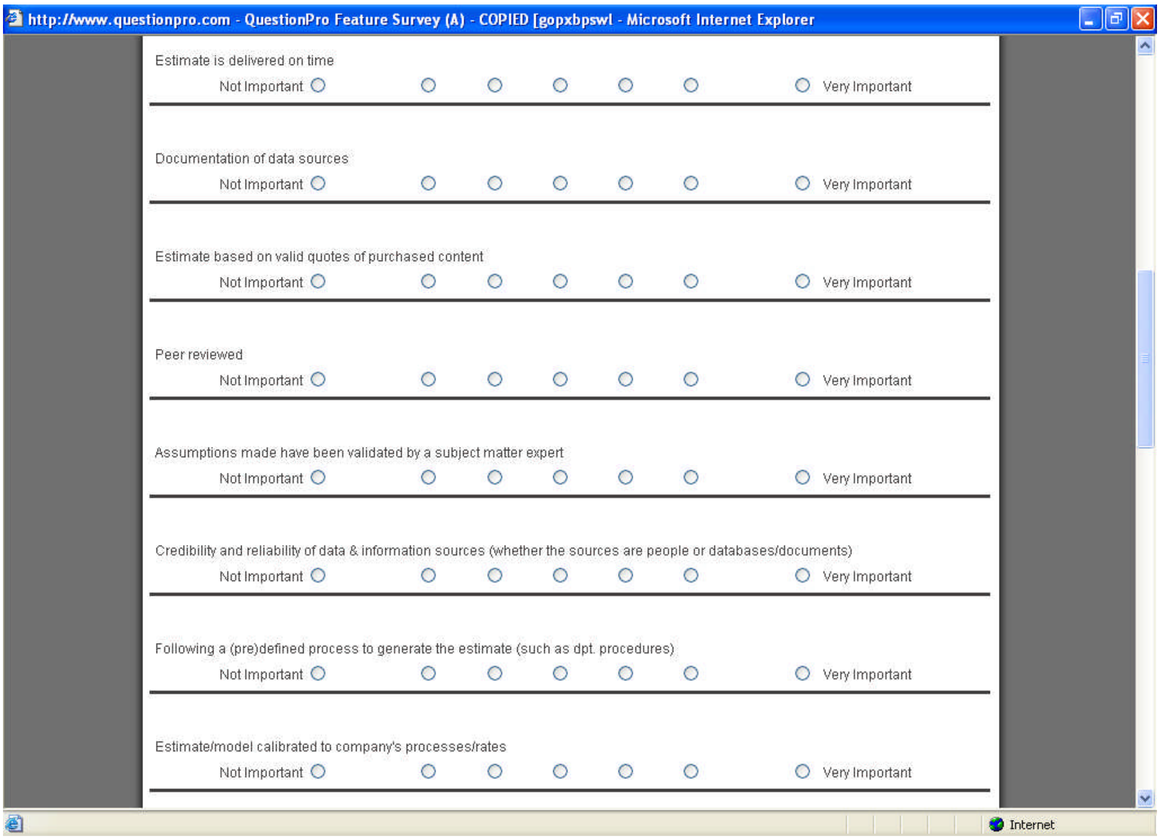
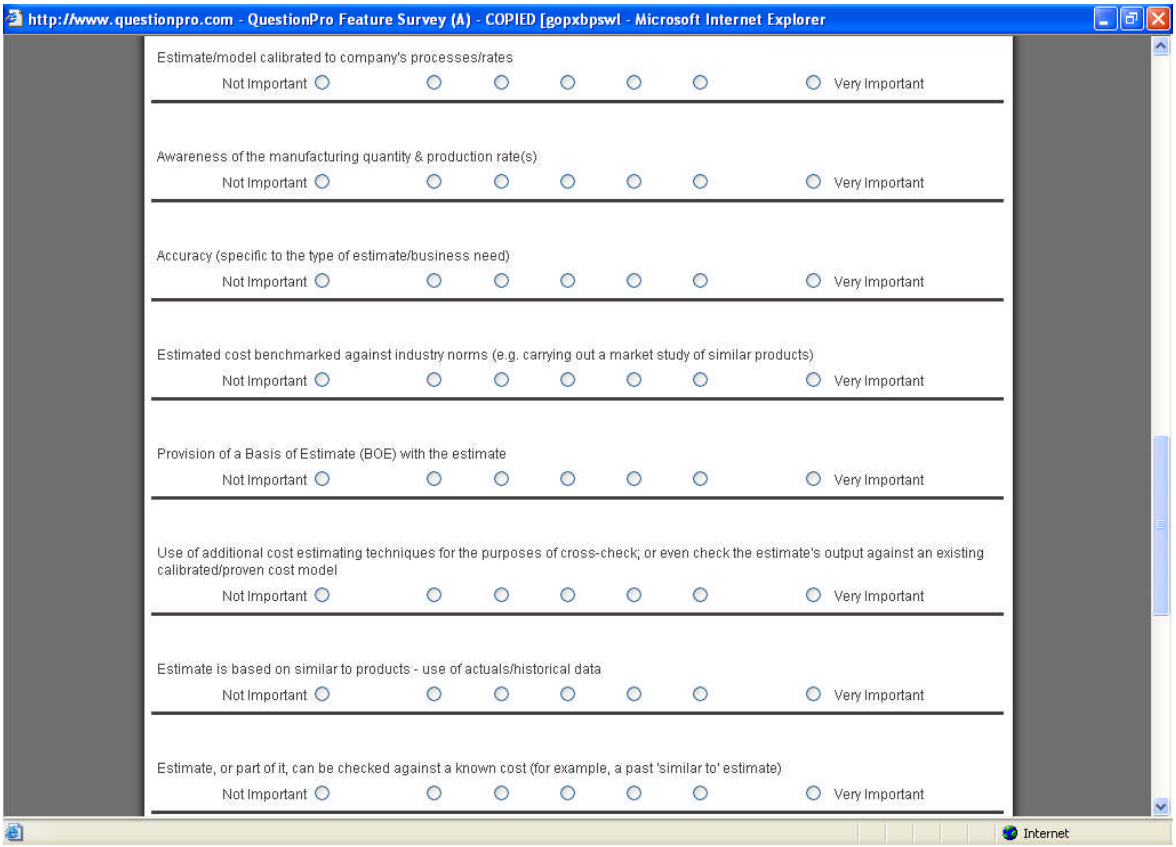


Figure A.3 – Second Part of Online Questionnaire (Page 2)


http://www.questionpro.com - QuestionPro Feature Survey (A) - COPIED [gopxbpswl - Microsoft Internet Explorer

Estimate/model calibrated to company's processes/rates
Not Important ○ ○ ○ ○ ○ ○ ○ Very Important

Awareness of the manufacturing quantity & production rate(s)
Not Important ○ ○ ○ ○ ○ ○ ○ Very Important

Accuracy (specific to the type of estimate/business need)
Not Important ○ ○ ○ ○ ○ ○ ○ Very Important

Estimated cost benchmarked against industry norms (e.g. carrying out a market study of similar products)
Not Important ○ ○ ○ ○ ○ ○ ○ Very Important

Provision of a Basis of Estimate (BOE) with the estimate
Not Important ○ ○ ○ ○ ○ ○ ○ Very Important

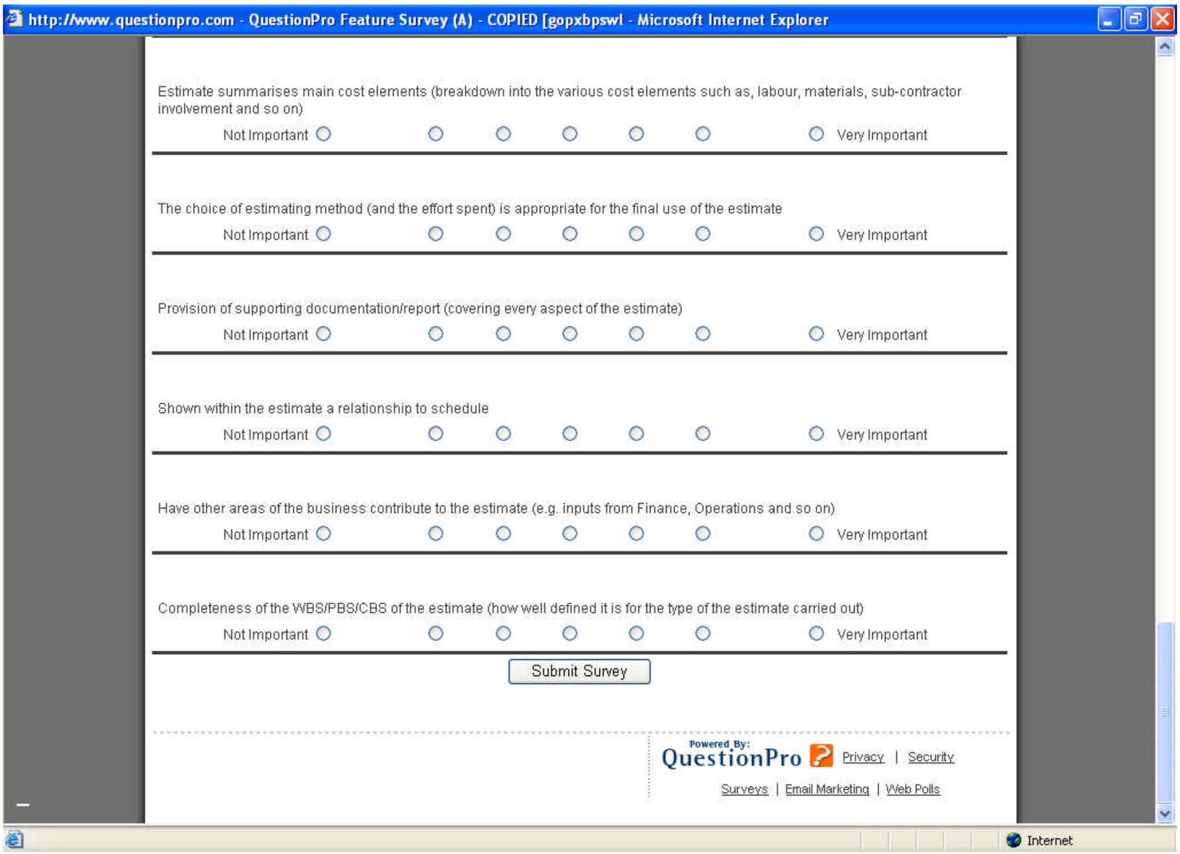
Use of additional cost estimating techniques for the purposes of cross-check; or even check the estimate's output against an existing calibrated/proven cost model
Not Important ○ ○ ○ ○ ○ ○ ○ Very Important

Estimate is based on similar to products - use of actuals/historical data
Not Important ○ ○ ○ ○ ○ ○ ○ Very Important

Estimate, or part of it, can be checked against a known cost (for example, a past 'similar to' estimate)
Not Important ○ ○ ○ ○ ○ ○ ○ Very Important

Internet

Figure A.4 – Second Part of Online Questionnaire (Page 3)


http://www.questionpro.com - QuestionPro Feature Survey (A) - COPIED [gopxbpswl - Microsoft Internet Explorer

Estimate summarises main cost elements (breakdown into the various cost elements such as, labour, materials, sub-contractor involvement and so on)
Not Important ○ ○ ○ ○ ○ ○ ○ Very Important

The choice of estimating method (and the effort spent) is appropriate for the final use of the estimate
Not Important ○ ○ ○ ○ ○ ○ ○ Very Important

Provision of supporting documentation/report (covering every aspect of the estimate)
Not Important ○ ○ ○ ○ ○ ○ ○ Very Important

Shown within the estimate a relationship to schedule
Not Important ○ ○ ○ ○ ○ ○ ○ Very Important

Have other areas of the business contribute to the estimate (e.g. inputs from Finance, Operations and so on)
Not Important ○ ○ ○ ○ ○ ○ ○ Very Important

Completeness of the WBS/PBS/CBS of the estimate (how well defined it is for the type of the estimate carried out)
Not Important ○ ○ ○ ○ ○ ○ ○ Very Important

Submit Survey

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Surveys | Email Marketing | Web Polls

Internet

Figure A.5 – Second Part of Online Questionnaire (Page 4)

A.4 Questionnaire for Framework Validation

In this Section, the questionnaire used by the author for eliciting the experts' feedback regarding the use of the proposed framework during the case studies, is presented.

Name:	
Estimate:	
Question	**Expert's Answer**
Do you agree with the information and knowledge captured within the templates?	
Do you think the framework has helped the novice to prepare a good estimate?	
Do you believe the use of the framework reduces the time of interaction with expert (i.e. by using the framework, the novice needs less guidance from expert(s))?	
Do you believe the final result (i.e. the estimated cost) is a good measure of how good the novice's estimate is?	
Do you think the templates and sheets provided within the framework can help a novice know what information he requires in order to prepare a cost estimate?	
Do you believe the templates (and the use of the framework) have allowed the capture such knowledge; so it can be reviewed by experts at a later stage?	
Do you think the use of the framework would contribute towards the formalisation of the cost estimating process?	
Do you believe the learning curve of novice cost estimators could be accelerated, by using the proposed framework?	
Do you have any recommendations on how to improve the effectiveness of the framework?	

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APPENDIX B – IDEF0 DIAGRAMS

B.1 IDEF0 Diagrams

As described in Chapter 4, the IDEF0 technique was selected in order to model the cost estimation process for a typical hardware product. In this Section the additional, to the ones already presented in Chapter 4, IDEF0 functions are presented along with a few supplementary notes regarding the IDEF0 modelling process.

Figure B.1 presents a typical function used within an IDEF0 model along with its Inputs, Controls, Outputs and Mechanisms.

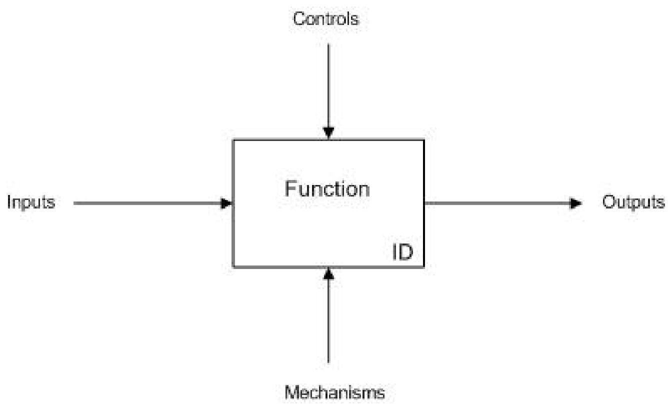


Figure B.1 – An Example of a Function and its ICOMs in IDEF0

Every function in IDEF0 has the following:

- **Inputs:** The inputs required to produce the output(s) of the function. They are always on the left side of the function box
- **Outputs:** The outputs of the function. Found on the right side of the function box
- **Mechanisms:** The means of supporting the execution of the function. Always on the bottom of the function box, facing upwards
- **Controls:** The conditions associated with the execution of that function (similar to constraints). Always on the top of the function box, facing downwards

The 'Produce Cost Estimate' process, at the Node A0 level, is described as:

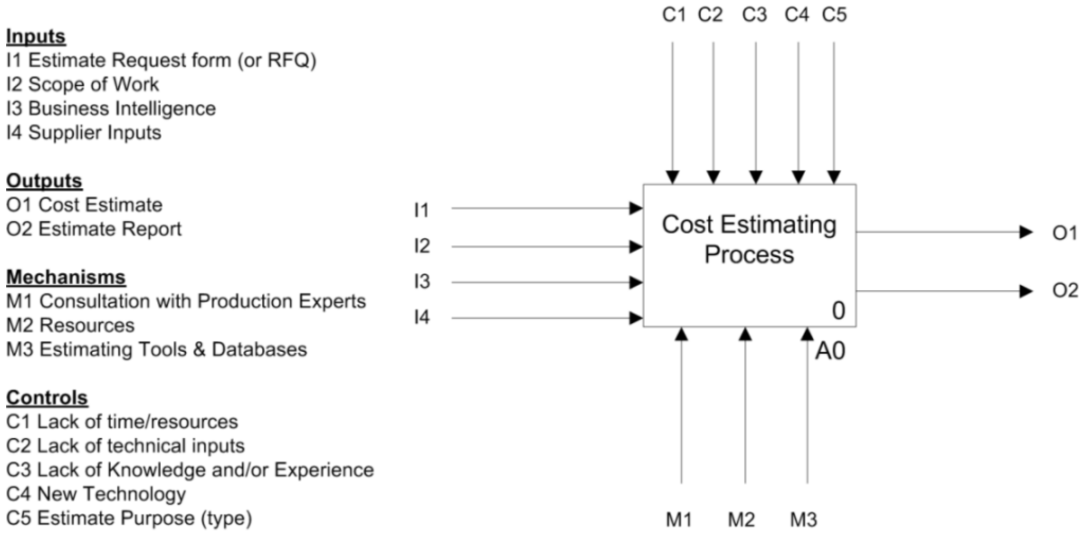


Figure B.2 – Cost Estimating Process Function

Figure B.3 presents a simple hierarchical diagram of how the IDEF0 functions relate to each other.

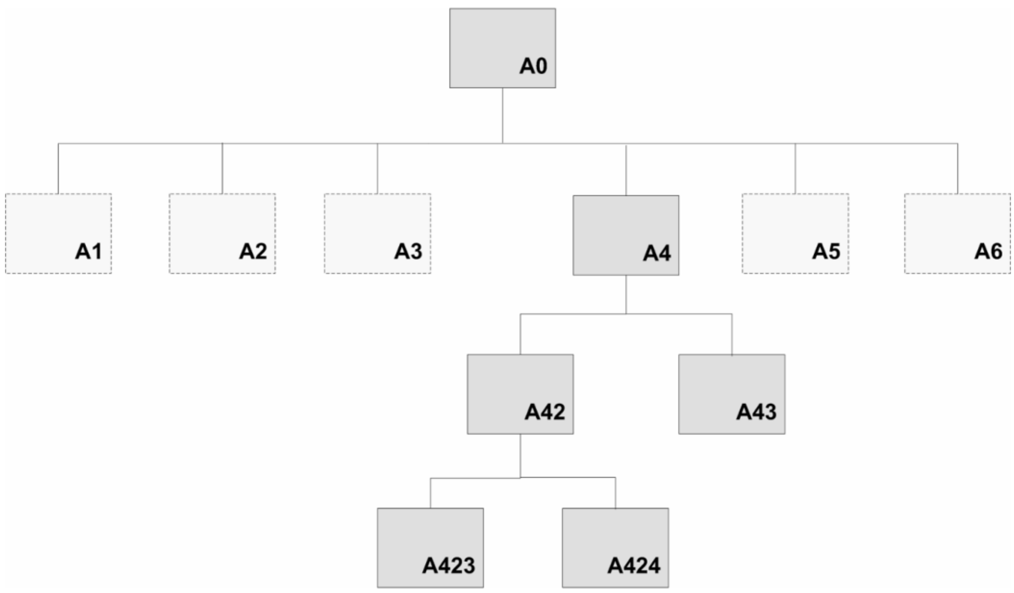


Figure B.3 – Hierarchical Decomposition of the IDEF0 nodes

Figures B.4, B.5, B.6, B.7, B.8 and B.9 present the lower level decomposition of the function presented in Figure B.2.

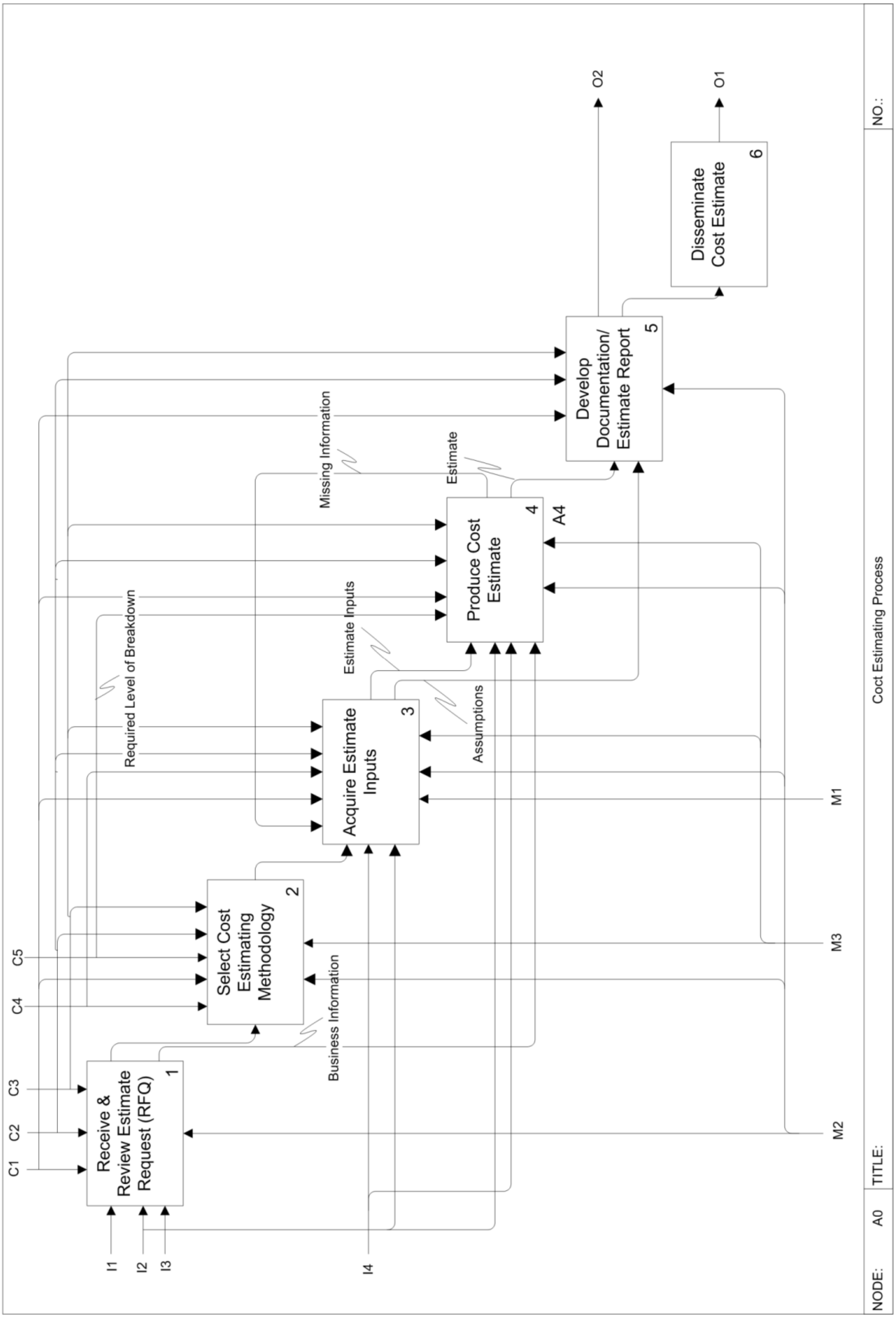


Figure B.4 – IDEF0 Diagram for Node A0

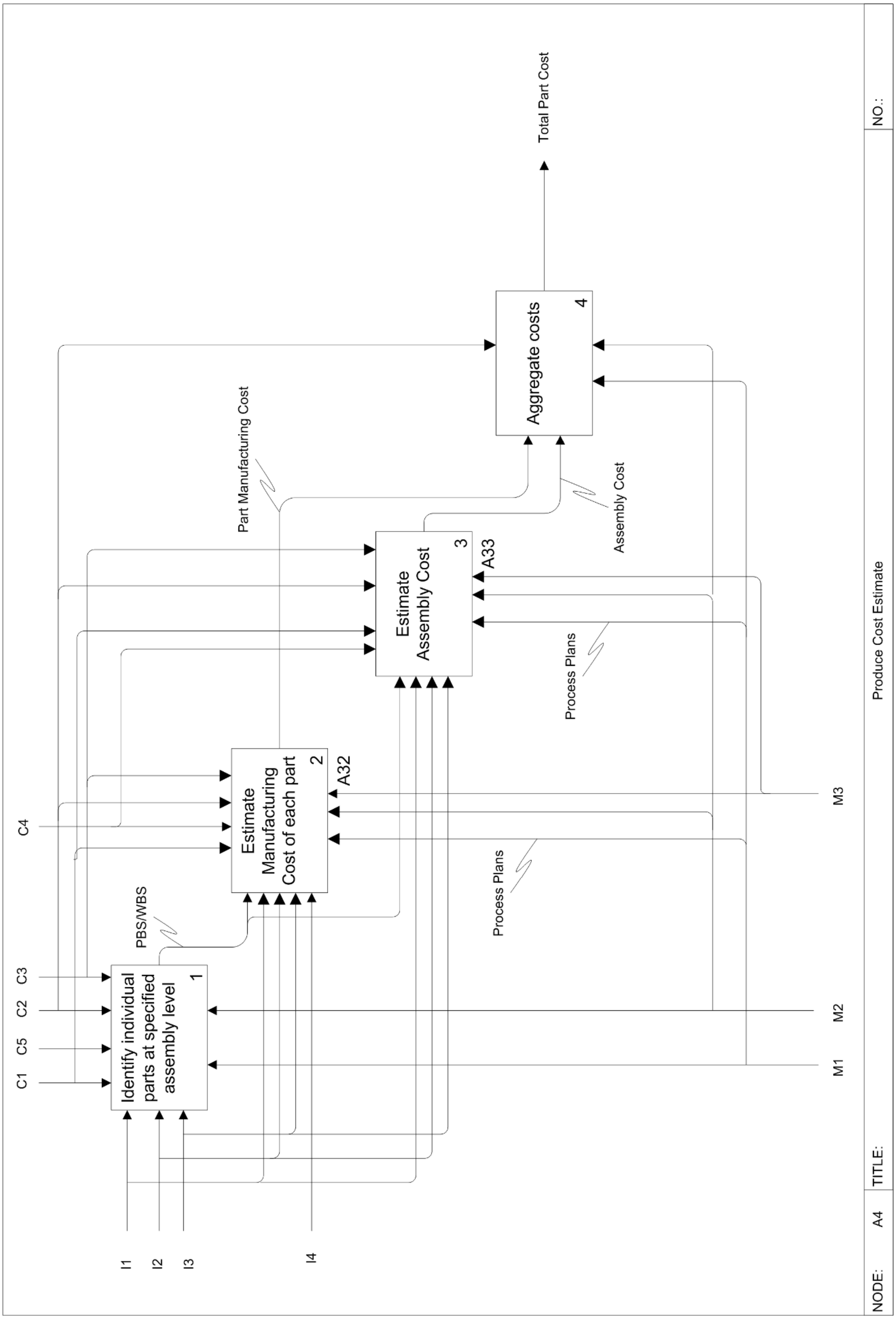


Figure B.5 – IDEF0 Diagram for Node A4

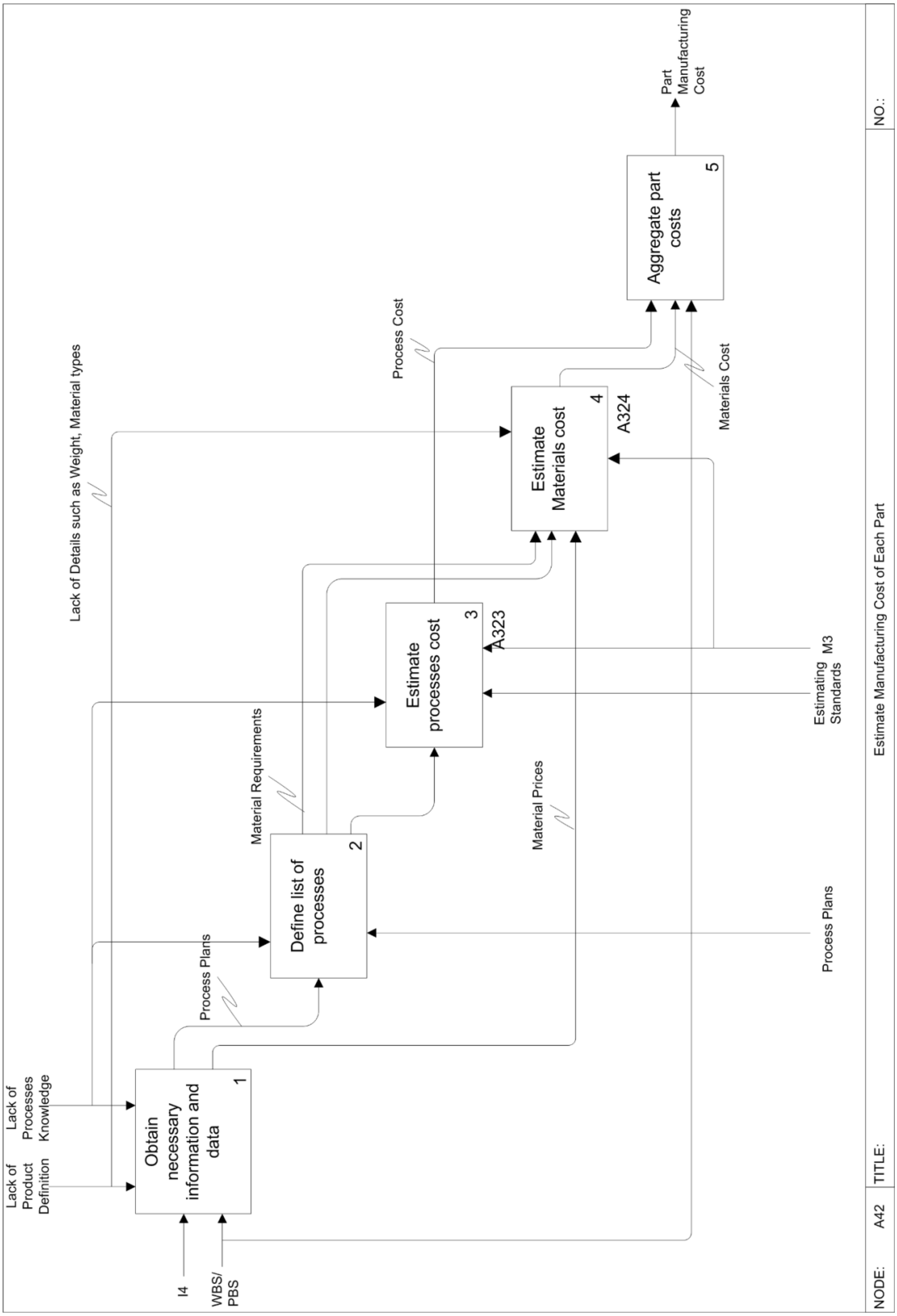


Figure B.6 – IDEF0 Diagram for Node A42

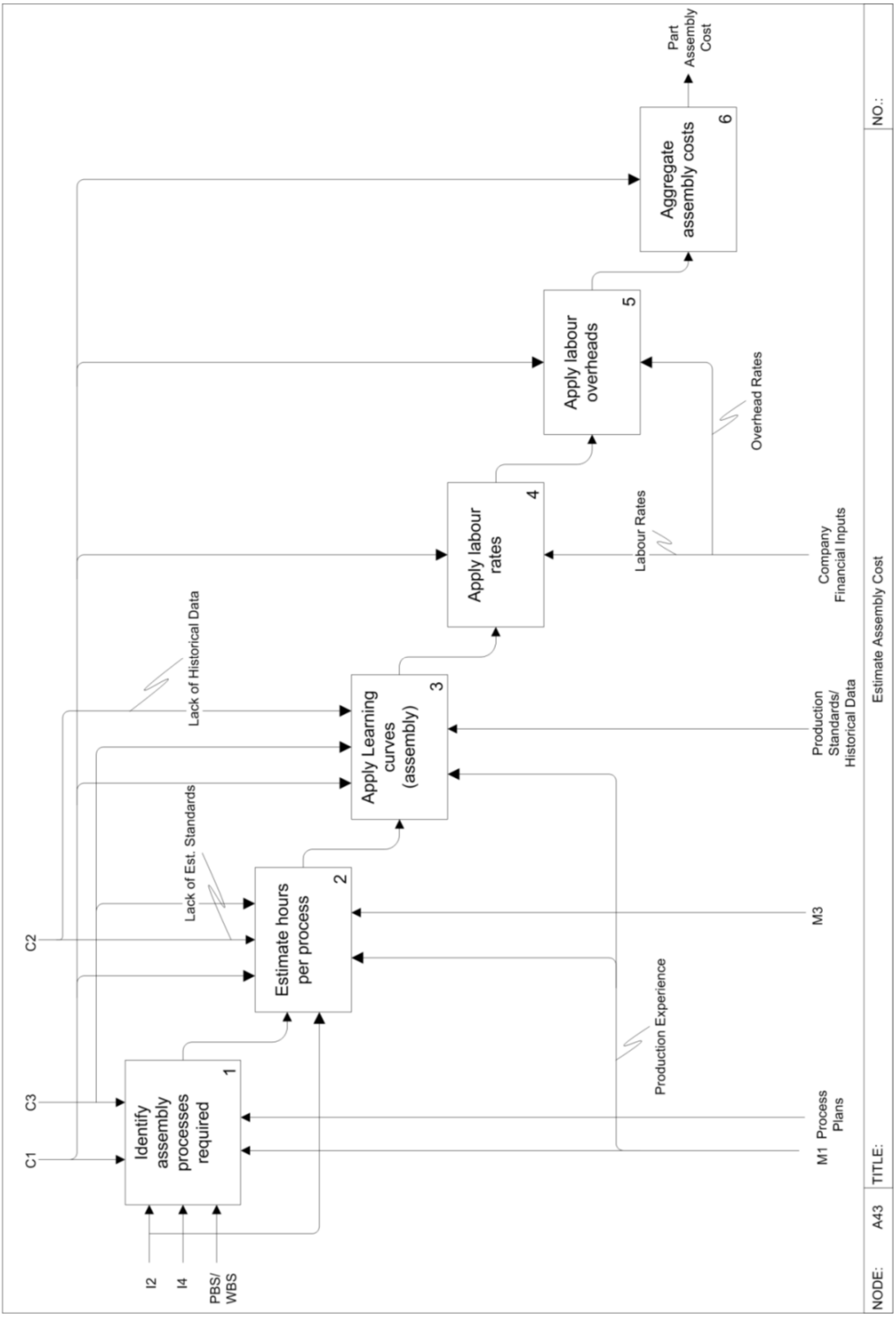


Figure B.7 – IDEF0 Diagram for Node A43

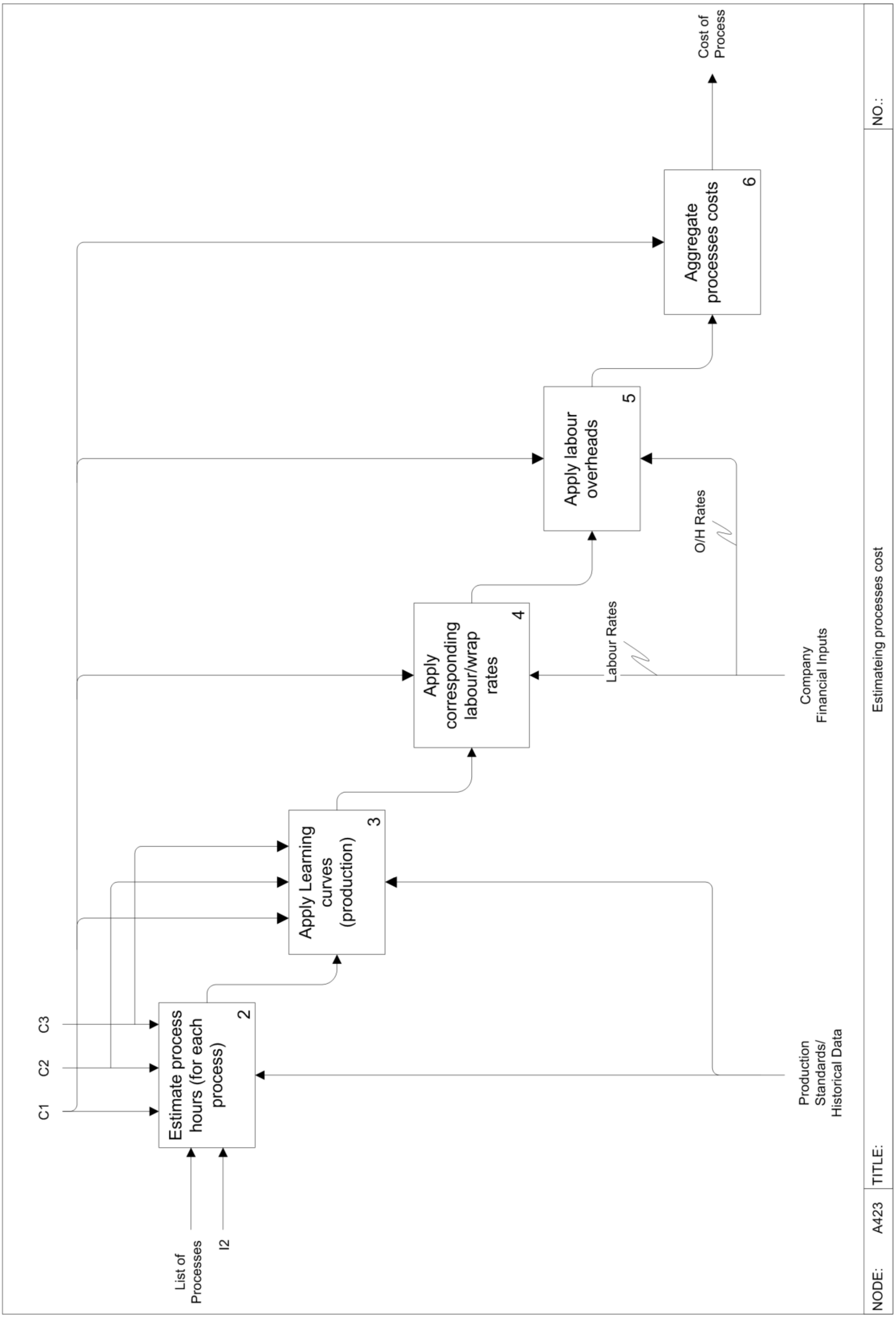


Figure B.8 – IDEF0 Diagram for Node A423

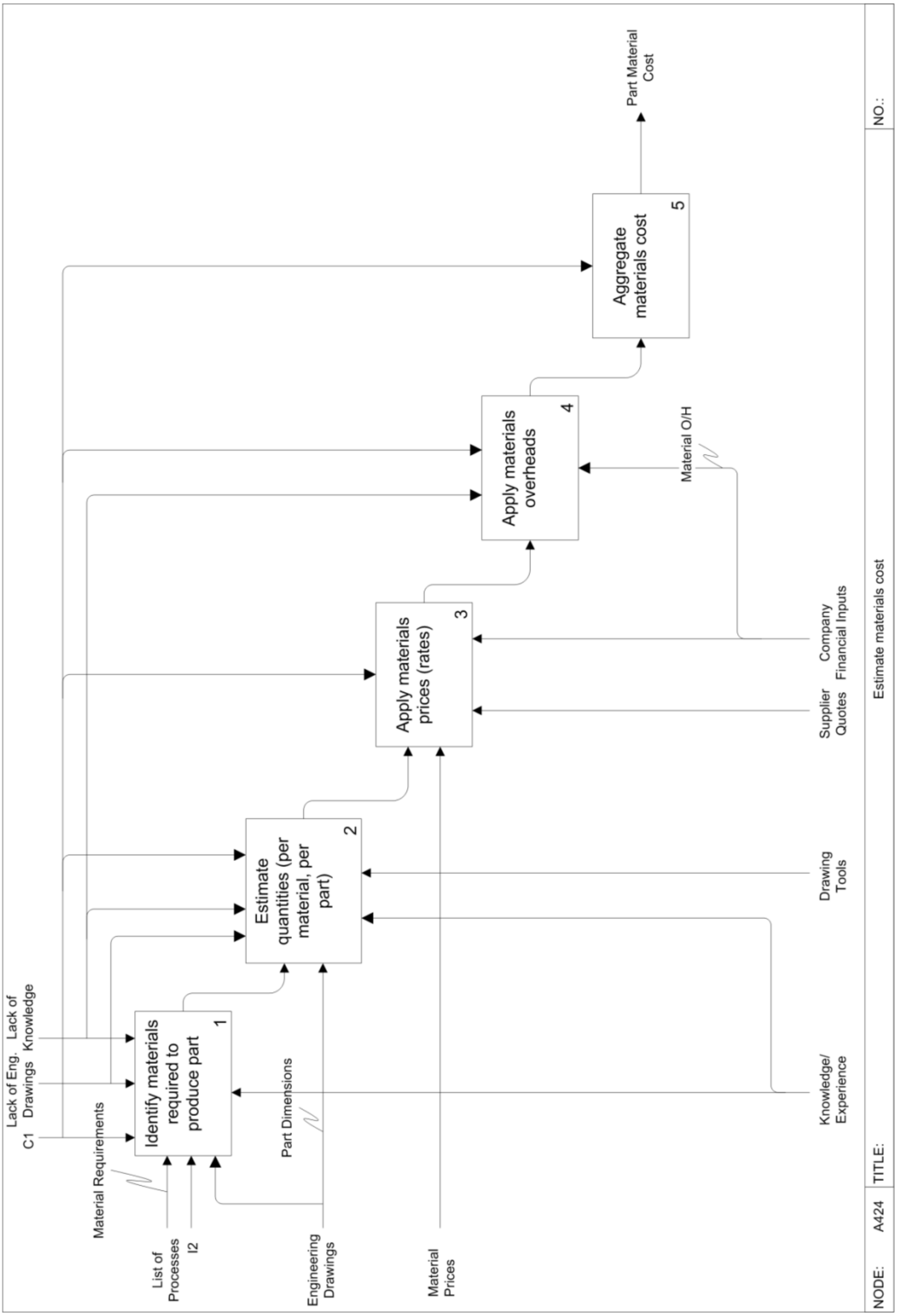


Figure B.9 – IDEF0 Diagram for Node A424

APPENDIX C – METHODOLOGY DEVELOPMENT & CASE STUDIES ADDITIONAL INFORMATION

C.1 Case study 1 – Fan Cowl Door

This Section presents any additional information regarding the Fan Cowl Door case study (supplementary to what has already been presented in Chapter 7).

C.1.1 Estimate Request

The novice received an estimate request (similar to the one the expert had received) for estimating the recurring unit cost for the production of a Fan Cowl Door. The estimate request form is presented in Figure C.1.

- There are typically 2-doors per engine set, however cost estimate is based on 1-door
- Door is fitted to 20,000lb thrust turbo-fan engine
- Engine is under-wing pylon mounted
- Engine is fitted to 120 seat commercial aircraft
- It is assumed for the purposes of the estimate that the market size is 500 production aircraft
- Whilst the delivery schedule for the doors and hence (the manufacturing cycle) spans 10 – 15 years cost estimate will be based on 2005 economic conditions
- Weight of door = 40kg
- Dimensions of developed door = 2.9m x 1.4m
- Door is carbon fibre and metallic honeycomb sandwich construction with metallic peripheral components such as hinges and latches
- Costs will be calculated in U.S.$ the currency of the aerospace industry

Figure C.1 – Fan Cowl Door Estimate Request

C.1.2 Supplementary Material on the Product & Associated Processes

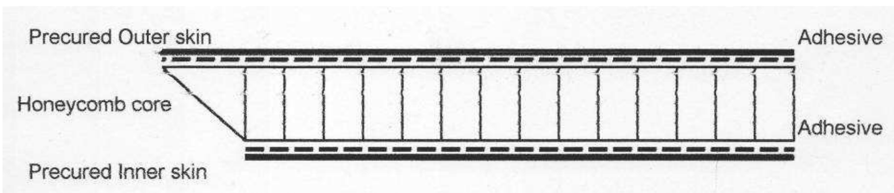


Figure C.2 – Section through Bonded Door Panel

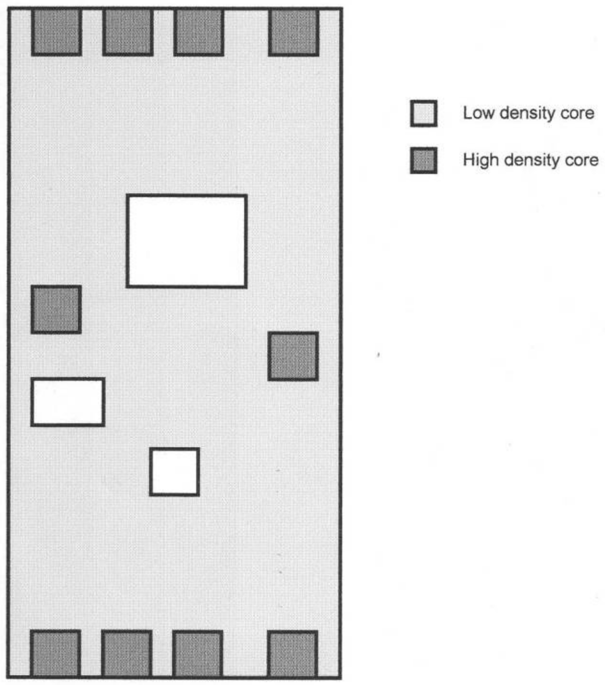


Figure C.3 – Diagram of Honeycomb Core

Part Ref	Description	Source	Method of Manufacture	Material Type	Qty/ door
1	Bonded panel	Manufactured	Composite sandwich	Carbon fibre and aluminium honeycomb	1
2	Pylon hinge	Manufactured	Machined	Stainless steel	4
3	Main latch	Purchased	-	-	4
4	Main latch housing	Manufactured	Machined	Stainless steel	4
5	Access door	Manufactured	Composite sandwich	Carbon fibre and aluminium honeycomb	1
6	Pressure relief door	Manufactured	Composite laminate	Carbon fibre	1
7	Ventilation grille	Purchased	-	-	1
8	Drains mast	Manufactured	Fabricated	Stainless steel	1
9	Pylon seal	Manufactured	Cut to length	Fire resisitant rubber	1
10	Pylon seal retainer	Manufactured	Fabricated	Stainless steel	1
11	Bottom seal	Manufactured	Cut to length	Fire resisitant rubber	1
12	Bottom seal retainer	Manufactured	Fabricated	Stainless steel	1
13	Forward seal	Manufactured	Cut to length	Fire resisitant rubber	1
14	Forward seal retainer	Manufactured	Fabricated	Stainless steel	1
15	Aft seal	Manufactured	Cut to length	Fire resisitant rubber	1
16	Aft seal retainer	Manufactured	Fabricated	Stainless steel	1
17	Hold open rod	Purchased	-	-	2
18	Hold open rod mounting bracket	Manufactured	Machined	Stainless steel	2
19	Hold open rod stowage bracket	Manufactured	Machined	Stainless steel	2
20	Hinge bolts	Purchased	-	-	24
21	Latch bolts	Purchased	-	-	32
22	Seal retaining fasteners	Purchased	-	-	350
23	Corner piece	Manufactured	Machined	Nylon	4

Figure C.4 – BOM of a Typical Fan Cowl Door

C.1.3 Templates

This Section presents the templates of the proposed framework, filled in by the author during the course of the case study carried out.

Structural Entity Templates

Structural Entity			
Name	Fan Cowl Door	**P/N**	[redacted]
Type (e.g. Ass., HW)	Assembly (HW)	**Hierarchical Level**	X.X.X
Function(s)	Allow easy access to engines		
Description	Part of the Engine Nacelle. 2 Door per Nacelle, with the ability to open them during engine maintenance operations		
Dimensions/Drawing	- See attached Drawings - Door weight ~ 40kg.		
In-house or Sub-contracted?	Mainly In-house; some parts sub-contracted		
Method of Manufacture/ Assembly	**Name**	Fan Cowl Door Mechanical Assembly	
	Description	The Bonded Door is placed on a Jig, where all the parts are assembled to form the complete Door.	
Information Source			
Related Parts	**Parent**	None	
	Child	X.X.X.1; X.X.X.2; X.X.X.3; X.X.X.4; X.X.X.5; X.X.X.6	
Related Operations Characteristics	'Fan Cowl Door Mechanical Assembly'		
Management	**Author**	E. Loukos	
	Date	[redacted]	
	Validation Status		

Figure C.5 – Structural Entity Template for the Fan Cowl Door

Structural Entity			
Name	Door Honeycomb Assembly	**P/N**	[redacted]
Type (e.g. Ass., HW)	Assembly	**Hierarchical Level**	X.X.X.1.1
Function(s)	see 'Fan Cowl Door'		
Description	—		
Dimensions/Drawing	See Drawings		
In-house or Sub-contracted?	Manufactured In-house		
Method of Manufacture/ Assembly	**Name**	Door Honeycomb Bonded Assembly	
	Description	The 2 skins are bonded together to form a sandwich assembly	
Information Source			
Related Parts	**Parent**	X.X.X.1	
	Child	X.X.X.1.1.1 and X.X.X.1.1.2	
Related Operations Characteristics	'Door Honeycomb Bonded Assembly'		
Management	**Author**	E. Landos	
	Date	[redacted]	
	Validation Status	Validated.	

Figure C.6 – Structural Entity Template for the Door Honeycomb Assembly

Structural Entity			
Name	Door Inner Skin	P/N	[redacted]
Type (e.g. Ass., HW)	HW/Part	Hierarchical Level	X.X.X.1.1.2
Function(s)			
Description			
Dimensions/Drawing	see Drawings		
In-house or Sub-contracted?	In-house.		
Method of Manufacture/ Assembly	Name	Composite Manufacturing	
	Description	Layers of Pre-Impregnated Carbon Fabric are layed on a tool to form the Inner Skin	
Information Source			
Related Parts	Parent	X.X.X.1.1.	
	Child	NONE	
Related Operations Characteristics	'Composite Manufacturing'		
Management	Author	G. Loudos	
	Date	[redacted]	
	Validation Status	Validated.	

Figure C.7 – Structural Entity Template for the Door Inner Skin

Structural Entity			
Name	Pylon Hinge	**P/N**	[redacted]
Type (e.g. Ass., HW)	HW Part	**Hierarchical Level**	X.X.X.1.2
Function(s)	To facilitate the opening of the Door; and carry its weight on the Pylon		
Description			
Dimensions/Drawing	N/A.		
In-house or Sub-contracted?	Sub-contracted.		
Method of Manufacture/ Assembly	**Name**	N/A	
	Description	usually manufactured as a forging	
Information Source			
Related Parts	**Parent**	X.X.X.1	
	Child	X.X.X.1.2.1	
Related Operations Characteristics			
Management	**Author**	E. Larchs	
	Date	[redacted]	
	Validation Status	Validated.	

Figure C.8 – Structural Entity Template for the Pylon Hinge

Structural Entity			
Name	Access Door Assembly	P/N	[redacted]
Type (e.g. Ass., HW)	Assembly (HW)	Hierarchical Level	X.X.X.2
Function(s)	To allow maintenance crew to monitor the engine, without opening all the fan Cowl Door		
Description			
Dimensions/Drawing	see Drawings.		
In-house or Sub-contracted?	In-house		
Method of Manufacture/ Assembly	Name	Composite Manufacturing	
	Description	Manufactured in the same way as the Door honeycomb	
Information Source			
Related Parts	Parent	X.X.X	
	Child	None	
Related Operations Characteristics			
Management	Author	E. Lowdas	
	Date	[redacted]	
	Validation Status	Validated.	

Figure C.9 – Structural Entity Template for the Access Door Assembly

Structural Entity			
Name	Ventilation Grille	**P/N**	[redacted]
Type (e.g. Ass., HW)	HW Part	**Hierarchical Level**	x.x.x.4
Function(s)	Allow ventilation of air from the nacelle		
Description			
Dimensions/Drawing	see Drawings.		
In-house or Sub-contracted?	out-sourced !!!		
Method of Manufacture/ Assembly	**Name**		
	Description		
Information Source			
Related Parts	**Parent**	x.x.x	
	Child	x.x.x.4.1	
Related Operations Characteristics			
Management	**Author**	C. Cordos	
	Date	[redacted]	
	Validation Status	Validated.	

Figure C.10 – Structural Entity Template for the Ventilation Grille

<table>
<tr><th colspan="5">Structural Entity</th></tr>
<tr><td>Name</td><td colspan="2">Hold Open Rod Assembly</td><td>P/N</td><td>[redacted]</td></tr>
<tr><td>Type (e.g. Ass., HW)</td><td colspan="2">Assembly (HW)</td><td>Hierarchical Level</td><td>X.X.X.6</td></tr>
<tr><td>Function(s)</td><td colspan="4">To hold the Fan Cowl Door into an 'open' position</td></tr>
<tr><td>Description</td><td colspan="4"></td></tr>
<tr><td>Dimensions/Drawing</td><td colspan="4"></td></tr>
<tr><td>In-house or Sub-contracted?</td><td colspan="4">OUT-SOURCED!</td></tr>
<tr><td rowspan="2">Method of Manufacture/ Assembly</td><td>Name</td><td colspan="3"></td></tr>
<tr><td>Description</td><td colspan="3"></td></tr>
<tr><td>Information Source</td><td colspan="4"></td></tr>
<tr><td rowspan="2">Related Parts</td><td>Parent</td><td colspan="3">X.X.X</td></tr>
<tr><td>Child</td><td colspan="3">X.X.X.6.1; X.X.X.6.2 and X.X.X.6.3</td></tr>
<tr><td>Related Operations Characteristics</td><td colspan="4"></td></tr>
<tr><td rowspan="3">Management</td><td>Author</td><td colspan="3">E. Lavdas</td></tr>
<tr><td>Date</td><td colspan="3">[redacted]</td></tr>
<tr><td>Validation Status</td><td colspan="3">Validated</td></tr>
</table>

Figure C.11 – Structural Entity Template for the Hold-Open Rod Assembly

Manufacturing Process Templates

Manufacturing Process					
Name	Composite Manufacturing (Door Skins)				
Manufacturing Process Description	Skin Plies are cut to size, and they are laid-up on the tool. Upon Completion, the composite Part is cured in a High Pressure Autoclave.				
Tooling Requirements	**Tool(s) Life**	—			
	Tool(s) Price	Tool already available			
Manufacturing Operations	**Name**		**Estimating Standard**	**Material Used**	**Wrap rates**
	1. Cut all skin plies		1min/m	Carbon Fabric	Composite Manuf.
	2. Lay-up Ply 1 (0/90°)		20-80min/m²		– " –
	3 Lay-up Ply 2 (+/-45°)		– " –		– " –
	4. Lay-up Ply 3 (0/90°)		– " –		– " –
	5. Bag-up & Vacuum Debulk		20min/m²		– " –
	6. Lay-up Plies 4-6		20-80min/m²		– " –
	7. Bag-up & Vacuum Debulk		20min/m²		– " –
	8. Lay-up Plies 7-9		20-80min/m²		– " –
	9. Bag-up & Vacuum Debulk		20min/m²		– " –
	10. Lay-up Plies 10 & 11		20-80min/m²		– " –
	11. Bag-up & Debulk for Cure		20min/m²		– " –
	12. Cure at High Pressure		WRAP Rate x (m²)		HP Autoclave
	13. Dismantle & Remove Part		25min/m²		Composite Manuf.
	14. Remove Adhesive Spew		3min/m		– " –
Materials Used	**Material Name**			**Material Price**	
	Pre-Impregnated Carbon Fabric			72 $/m²	
Information Source					
Related Processes	**Parent**				
	Child				
Management	**Author**	E. Lavdas			
	Date	[redacted]			
	Validation Status	Validated			

Figure C.12 – Manufacturing Process Template for the Composite Manufacturing (Laminate of Door Skins)

Manufacturing Process				
Name	Fan Cowl Door Mechanical Assembly			
Manufacturing Process Description	Bonded Door is placed on a jig, where all the parts are mounted.			
Tooling Requirements	**Tool(s) Life**	—		
	Tool(s) Price	Jigs already available		
Manufacturing Operations	**Name**	**Estimating Standard**	**Material Used**	**Wrap rates**
	1. Place Assembly on Jig			Assembly
	2. Locate Hinges & Drill	6 per min		— " —
	3. Apply Sealant to Hinge faces			— " —
	4. Bolt 4 hinges in place	2 per min	Hinge Bolts	— " —
	5. Fit Access Doors & set gaps	18 min/m		— " —
	6. Fit Pres. Relief Doors & set gaps	18 min/m		— " —
	7. Fit Ventilation Grille			— " —
	8. Locat seal retainers & Drill	6 per min		— " —
	9. Install Seal Retainers Fasteners	4 per min	Seal fasteners	— " —
	10. Fit Drains Mast			— " —
	11. Set Main Door Gaps	12 min/m.		— " —
	12. Fill Surface & Rub Down	60 min/m²	Filler	— " —
	13. Apply Primer	10 min/m²	Primer	— " —
	14. Apply Finish Paint	12 min/m²	Finish Paint	— " —
Materials Used	**Material Name**		**Material Price**	
	Filler		28 $/kit	
	Primer		26 $/lt	
	Finish Paint		34 $/lt	
	Hinge Bolts		2.8 $ (each)	
Information Source	Seal fasteners		0.52 $ (each)	
Related Processes	**Parent**			
	Child			
Management	**Author**	E. Lardos		
	Date	[redacted]		
	Validation Status	Validated.		

Figure C.13 – Manufacturing Process Template for the Fan Cowl Door Mechanical Assembly

Manufacturing Process				
Name	Door Honeycomb Bonded Assembly			
Manufacturing Process Description	The two composite skins are assembled in forming a honeycomb core (Bonded assembly)			
Tooling Requirements	**Tool(s) Life**	—		
	Tool(s) Price	Tool already Available		
Manufacturing Operations	**Name**	**Estimating Standard**	**Material Used**	**Wrap rates**
	1. Prepare Tool (with Release Agent)	40min/m^2		Composite Manuf.
	2. Cut Foaming Adhesive to length	10min/m		Composite Manuf.
	3. Cut 11 Foam Pieces to size	5min/m	L&H Density Core	—"—
	4. Assemble Pieces with Adhesive	32min/m^2	Foaming Adhesive	Assembly
	5. Bagging & Vacuum Debulks	20min/m^2		Composite Manuf.
	6. Cure at Low Pressure	Wrap Rate x (m^2)		LP Autoclave
	7. Dismantle & Remove Part	25min/m^2		Composite Manuf.
Materials Used	**Material Name**		**Material Price**	
	Low Density Honeycomb		85 \$/m^2	
	High Density Honeycomb		105 \$/m^2	
	Foaming Adhesive		23 \$/m^2	
Information Source				
Related Processes	**Parent**			
	Child			
Management	**Author**	C. Lanitos		
	Date	[redacted]		
	Validation Status	validated.		

Figure C.14 – Manufacturing Process Template for the Door Honeycomb Bonded Assembly

Assumptions Sheet

Ass. #	Points where Novice got Stuck	Assumption Made	Question generated (if Applicable)	Expert's Response
1		An assumption given by the Expert during the initial meeting was that carbon fabric reels come in 1.5 m width.		Expert's assumption
2	During the calculation of the Outer Skin Door lay-ups, I cannot understand from the drawings given whether there are 4 or 11 lay-ups	The assumption was made that there are 11 lay-ups	How many lay-ups are there in total for the Outer Door Skin?	There are 11. Same as the assumption made by the Novice.
3	For the lay-up time of Ply 2 for the Outer Skin, the Novice was not sure what time to use. The Expert had given him that it varies from 20 to 80 min/m2 depending on contour.	The Novice assumed that although the contour isn't complicated, the time will be 30 min due to that Lay-up being placed in an angle.		Assumption presented to Expert and was found to be realistic.
4	When the Novice started making calculations for the Autoclave curing the only information that he was given was the cost per m2 of part. However he was not sure whether he should consider the area of only one side of the part, or the total area.	The assumption was made to take into account both sides of part.	When it comes to applying the Warp rates for the autoclave do I take the area of one side of the part, or of both sides?	The Expert said that you take the area of only one side. The Novice went back to the estimate and corrected the autoclave costs.
5	For the Door Inner skin the Novice wasn't sure if you could use the remaining of the fabric used for the last ply 4-8 at the Outer Skin.	The Novice assumed you do, based that there was enough material left to be able to cover that area.		The Expert looked into the logic of the assumption and found it to be a sound assumption.
6	When it comes to cutting the foaming adhesive, I was not given a time that this operation is going to take.	I assumed that it takes about 1 minute per meter, based on my experience.		Assumption presented to Expert and was found to be realistic.
7	For the assembly of the honeycomb cores I was not given a process time by the Expert.	I assumed it takes about 20min/part to assemble the cores (with the adhesive). In total there are 10 core parts.		Assumption presented to Expert and was found to be realistic.
8	When it comes to assembling the skins to form the Bonded Door Panel I am not sure whether this is considered as a manufacturing or an assembly operation. This would have an effect on what labour rate to use.	The assumption was taken that this is considered as an assembly cost.		
9	For the access panel door, I was not sure whether we use LD or HD core. I had no information given.	I assumed you use LD core due to the low-stress importance of this part. That was based on my own interpretation.		The Expert looked into the logic of the assumption and found it to be a sound assumption.
10	One of the operations is placing the door assembly on the jig. I was not given any information about that.	I made the assumptions that it takes around 30 minutes (per door) to place it on the jig.	I have assumed that it takes 30min/door to place the bonded assembly on the jig. Does this sound right to you?	Assumption presented to Expert and was found to be realistic.
11	When it comes to assembling the 2 brackets on the bonded panel, I was given drilling times and time to fit fasteners. However I do not know how many holes they have to be drilled.	Looking at the pictures provided by the expert (about a typical bracket for Fan Cowl Doors), I can see that there are 6 holes/bracket.		The Expert looked into the logic of the assumption and said that this is what he should have done too, and the assumption is sound.
12	For filling the surface of the bonded door assembly and rubbing down, I am not sure whether this applies to both side of the door, or just the exterior side.	The assumption was made that both sides are filled and rubbed down.	Are both sides of the bonded panel filled and rubbed down?	The Expert answered that 'yes, both sides are'; so the assumption is valid.
13	Not sure when doing the calculations for painting & finishing whether this is assumed as an assembly or a manufacturing cost.	I assume it is an assembly cost	Is painting & finishing considered as an assembly operation, or do I consider it as a manufacturing operation?	
14	I was not told what the width of the seal retainers is; I know the length but I need also the width to calculate the forming time.	I assumed that the width of a seal retainer is around 3cm		Assumption presented to Expert and was found to be realistic.
15	As far as the Pylon Hinge and Main latch Housing is concerned I do not know how they are manufactured and what the operations are, because I was not given any information about them.	So I just assumed that they are bought as materials from the supplier, and assigned an estimated price to them based on the price of the forgings.		The Expert said that for both of them they buy a steel forging from the supplier. The only operations they will have to do will be to drill the holes and machine the base face of them to make it flat. However he agrees with the values that I used and there is no need to modify my estimate.

Figure C.15 – Assumption Sheet for the Fan Cowl Door Cost Estimate

C.2 Case Study 2 – Rib Assembly

This Section presents any additional information regarding the Rib Assembly case study (supplementary to what has already been presented in Chapter 8).

C.2.1 Estimate Request – RFQ Response

An estimate request was presented to the novice for estimating the production unit cost for a rib assembly. Some of the conditions made explicit within the request are:

- Production Quantity = 150 units
- Delivery Rate = 50 per Year
- All costs presented in $ US, for the three consecutive production years

An understanding of the conditions of the request is crucial in order to develop a cost estimate that reflects the customer requirements. Such conditions were also captured in the 'Estimate Cover Sheet' presented in Chapter 8, Figure 8.2.

C.2.2 Templates

This Section presents the templates of the proposed framework, filled in by the author during the course of the case study carried out in the collaborating organisation. Figure C.16 presents a typical Master Plan; a number of the fields were blanked by the author to protect any company proprietary information. Master Plans contain a plethora of information regarding the manufacturing operations, materials used, quality standards and so on. Thus, they are a valuable source of information that a cost estimator could tap into.

```
---------------------------------------------------------------------------
 PRINT DATE : [redacted]                                       PAGE :    3
             H E L L E N I C   A E R O S P A C E   I N D U S T R Y

                          M A S T E R   P L A N

 PRG : [redacted]  PN : [redacted]                  DETAIL KEY : [redacted]
---------------------------------------------------------------------------
        N  .                                                            99
        N  INSPECT THE TOUCH-UP PROCESS PER [redacted]                  99
===========================================================================
040  OP.CODE:[redacted]  SHOP:[redacted]000 RUN HRS: [redacted] SET HRS: [redacted] QC:N B.C:Y C:Y

       [redacted]                  CH VIDEO JET INK (  9999.00        Y   99
       [redacted]                  CH VARNISH FOR INK  9999.00        Y   99
       [redacted]                  CH VARNISH FOR INK  9999.00        Y   99
        N  IDENTIFY: INK STAMP PER [redacted]                           99
        N  POSITION: OPTIONAL                                           99
===========================================================================
050  OP.CODE:[redacted]  SHOP:[redacted]000 RUN HRS: [redacted] SET HRS: [redacted] QC:Y B.C:N C:Y
        N  INSPECT: VERIFY INK STAMPING PER [redacted]                  99
        N  INSPECT FINAL.                                               99
===========================================================================
060  OP.CODE:     SHOP:[redacted]000 RUN HRS: [redacted] SET HRS: [redacted] QC:N B.C:N C:Y
        N  STOCK PARTS FOR SHIPPING                                     99
        N  CLOSE ORDER TO SCHEDULE ORDERS CONTROL                       99
```

Figure C.16 – Example of a Typical Master Plan

Structural Entity			
Name	Rib	P/N	classified
Type (e.g. Ass., HW)	Hardware	Hierarchical Level	Level 4 - X.X.X.1
Function(s)	Part of the rib assembly; Major load carrying structure.		
Description			
Dimensions/Drawing	For Rib Dimensions, see 'Rib Assembly'. The pre-cut Aluminium block is bought from suppliers.		
Entity Source	Machined In-house		
Method of Manufacture/ Assembly	Name	High Speed Machining	
	Description	The rib is machined on a MAKINO CNC, from a pre-cut block of Al 7075.	
Information Source	Expert A & Master Plans.		
Related Parts	Parent	'Rib Assembly'	
	Child	None	
Related Operations Characteristics	see 'High Speed Machining' template.		
Management	Author	E. Lourdas	
	Date	[redacted]	
	Validation Status	Info Validated by Expert.	

Figure C.17 – Structural Entity Template for the Rib

Structural Entity			
Name	Support Assembly	P/N	classified.
Type (e.g. Ass., HW)	Assembly	Hierarchical Level	level 4-x.x.x.2
Function(s)	-Used to provide a support point for hydraulic lines and/or electrics.		
Description	The support looks like a typical 90° angled bracket, and is fixed on the 'Rib'.		
Dimensions/Drawing			
Entity Source	- Assembled In-house		
Method of Manufacture/ Assembly	Name	Assembly.	
	Description	The angle is located on the bracket and clamped, where 6 holes are drilled and rivets are installed to keep the 2 parts together.	
Information Source			
Related Parts	Parent	'Rib Assembly'	
	Child	'Angle' & 'Bracket'	
Related Operations Characteristics	see 'Assembly of Support' template.		
Management	Author	C. Loudas	
	Date	[redacted]	
	Validation Status	Validated by Expert	

Figure C.18 – Structural Entity Template for the Support Assembly

Structural Entity			
Name	Bracket	P/N	classified.
Type (e.g. Ass., HW)	Hardware.	Hierarchical Level	level 5-x.x.x.2.2
Function(s)			
Description			
Dimensions/Drawing			
Entity Source	Manufactured In-house.		
Method of Manufacture/ Assembly	Name	Forming	
	Description	Cut from sheet of AL 6061, formed into shape and then heat treated for increasing its strength.	
Information Source	Expert & Master Plan.		
Related Parts	Parent	'Support Assembly'	
	Child	None	
Related Operations Characteristics	See 1. 'Forming (Bracket)' and 2. 'Heat Treatment' templates.		
Management	Author	E. Lordos	
	Date	[redacted]	
	Validation Status	Validated by Expert.	

Figure C.19 – Structural Entity Template for Bracket

Structural Entity			
Name	Angle	P/N	classified.
Type (e.g. Ass., HW)	HW	Hierarchical Level	level 5-X.X.X.2.1
Function(s)			
Description			
Dimensions/Drawing	Layout is 6x8 inches, out of a .040" thick sheet		
Entity Source	Manufactured In-house		
Method of Manufacture/ Assembly	Name	Forming	
	Description	The layout of the angle is cut from a sheet of AL2024, and formed into shape on a power brake machine.	
Information Source	Expert & Master Plan		
Related Parts	Parent	'Support Assembly'.	
	Child	None.	
Related Operations Characteristics	See: 'Forming (Angle)' template.		
Management	Author	C. Londos	
	Date	[redacted]	
	Validation Status	Validated by Expert	

Figure C.20 – Structural Entity Template for the Angle

Manufacturing Process

Manufacturing Process				
Name	FORMING (ANGLE)			
Manufacturing Process Description	The angle is fabricated by first cutting the required layout in a Trumpf machine and the forming it into shape.			
Tooling Requirements	Tool(s) Life	MSDF - Lasts throughout all production period		
	Tool(s) Price	NRC - Not Estimated.		
Manufacturing Operations	Name	Estimating Standard	Material Used	Wrap rates
	1. Trumpf	3 Not Estimated	Al2024 T3	FAB rate
	2. Remove Tabs	0.1 hr.		-"-
	3. Deburr	0.0333 hr.		-"-
	4. Attach Metal Tag	0.1 hr.		-"-
	5. Set up machine	0.5hr/lot (lot=10 parts)		-"-
	6. Setup part on Machine	0.05/part		-"-
	7. Power Break Part	0.05/part		-"-
	8. Chromate	Under S.P.		
	9. Apply Primer		Primer Epoxy	
	10. Apply Stamp/varnish	0.1/stamp.	Video Ink + Varnish	-"-
Materials Used	Material Name		Material Price	
	Al 2024 T3 .040" (6"x8")		1.093 $/part	
	Primer Epoxy		1.072 $	
	Video Jet Ink		1.072 $	
	Varnish		1.072 $	
Information Source	Master Plan & BOM & Expert.			
Related Processes	Parent	'Support Assembly'.		
	Child	None.		
Management	Author	E Lavdas		
	Date	[redacted]		
	Validation Status	Validated.		

Figure C.21 – Manufacturing Process Template for Forming (Angle)

Manufacturing Process					
Name	Forming (Bracket).				
Manufacturing Process Description	[illegible] to bracket [illegible]				
Tooling Requirements	Tool(s) Life	MSDF, TRSH, HPFM, HNFM (Last for the whole production Period).			
	Tool(s) Price	-Non Recurring Cost -Not Estimated/falls under 'Client Investment'			
Manufacturing Operations	Name	Estimating Standard	Material Used	Wrap rates	
	1. Traupf machine Drill [illegible] (x1)	- Not Estimated (stated by Expert)			
	2. " drill [illegible] (x2)	- Cost distributed to overheads.			
	3. " [illegible] .098"				
	4. Remove 1 tab [illegible]	0.[illegible] tab	—	FAB. rate	
	5. Scribe & trim line	0.01 hr	—	– " –	
	6. Deburr	0.033 hr.	—	– " –	
	7. Attach metal tag	0.1 hr.	—	– " –	
	8. [illegible] (Set A)	0.08 hr.	—	– " –	
	9. Check & straight / Deburr	0.03+0.033	—	– " –	
	10. Remove tabs & Deburr		—	– " –	
	11. Power brake/form 2 flanges [illegible]	0.05 hr	—	– " –	
	12. form parts in 2 stages	0.08	—	– " –	
	13. [illegible]		—	– " –	
	14. Heat treat	(see heat treatment)			
Materials Used	Material Name		Material Price		
	Raw Material 6061 (120x80) [illegible]		0.791 $/ bracket		
	Primer (Red)		1.092 $		
	Video Jet Ink		1.092 $		
	Varnish for Ink		1.092 $		
Information Source	Master Plan & BOM & Expert (for times).				
Related Processes	Parent	'Support Assembly'			
	Child	'Heat Treatment'			
Management	Author	C [illegible]			
	Date	[redacted]			
	Validation Status	Validated			

15. Big Inspection.
16. Chromate conversion (Alodine 1200S). Under S.P.
17. Apply coat of red epoxy primer.
~~[illegible]~~
19. Inspect Primer & Apply Stamping + Varnish
20. Inspect Stamping + forward to stock 0.1 hr

Figure C.22 – Manufacturing Process Template for Forming (Bracket)

Manufacturing Process				
Name	Heat Treatment			
Manufacturing Process Description	Required for bracket; cos bracket Aluminium is 'O', not heat treated, so it's malleable easily			
Tooling Requirements	Tool(s) Life	None		
	Tool(s) Price	None.		
Manufacturing Operations	Name	Estimating Standard	Material Used	Wrap rates
	1. Heat treat in Oven	Not Estimated - fall under Forming SP → 10% of M-H.	None	Same as Aerostruct
	2. Refrigerate			
	3. Check & Straighten			
	4. Vapor Degrease			
	5. Artificial Aging to T62			
	6. Back to Forming			
Materials Used	Material Name	Material Price		
Information Source	Master Plan & Expert.			
Related Processes	Parent	'Forming (Bracket)'		
	Child	None		
Management	Author	C. Lucas		
	Date	[redacted]		
	Validation Status	validated.		

Aging must be done 96hr after solution heat treatment.

Figure C.23 – Manufacturing Process Template for Heat Treatment

Manufacturing Process	
Name	HIGH SPEED MACHINING
Manufacturing Process Description	The raw material is loaded to a MAKINO CNC machine for machining. The machine is setup once for the lot (lot=12 ribs).

Tooling Requirements		
	Tool(s) Life	Drill Jig (PRJI) - Last all Production Period
	Tool(s) Price	NRC

Manufacturing Operations	Name	Estimating Standard	Material Used	Wrap rates
	1. Attach tkyp Tag	0.1/tag		FAB rate
	2. Set-up Machine	0.5hr/lot (lot=12)		– " –
	3. Machining	1.53hr/part	Al 7075	– " –
	4. Deburr	0.2hr		– " –
	5. Drill holes (x4) 0.280	0.083/hole		– " –
	6. Deburr holes (x4)			– " –
	7. Remove Mismatch	Minimal		– " –
	8. Clean Part	S.P.		
	9. Mask Area			

Materials Used	Material Name	Material Price
	Al 7075 pre-cut block	333.46$/rib

Information Source	Master Plan & BOM & Expert	
Related Processes	Parent	Rib Assembly
	Child	None
Management	Author	E. Londas
	Date	[redacted]
	Validation Status	Validated.

Figure C.24 – Manufacturing Process Template for High Speed Machining

Manufacturing Process				
Name	RIB ASSEMBLY			
Manufacturing Process Description	The Rib is located on tool where the support assembly is installed. The assembly is the primed and stamped.			
Tooling Requirements	**Tool(s) Life**	Last all duration of Production.		
	Tool(s) Price	NRC.		
Manufacturing Operations	**Name**	**Estimating Standard**	**Material Used**	**Wrap rates**
	1. Locate Parts on tool			ASS Rate
	2. Drill holes to size (x5)	0.0333/hole		– " –
	3. Disassemble & Deburr	0.0333/hole		– " –
	4. Clean for Glue Bond	S.P.		–
	5. Install all Items	0.166/assembly		– " –
	6. Touch-up Primer Epoxy	S.P.	Primer Epoxy	–
	7. Stamp Ink	0.1 hr/Stamp	Video Ink Jet	– " –
Materials Used	**Material Name**		**Material Price**	
	Rivets (x5)		0.06$/5 rivets	
	Nutplate (x1)		2.229$/nutplate	
	Primer Epoxy		1.072$/assembly	
	Video Ink Jet		1.072$/stamp	
Information Source	Master Plan & BOM & Expert.			
Related Processes	**Parent**	None		
	Child	'Machining High speed' & 'Support Assembly'		
Management	**Author**	G. Lourdes		
	Date	[redacted]		
	Validation Status	Validated.		

Figure C.25 – Manufacturing Process Template for Rib Assembly

Manufacturing Process				
Name	Support Assembly.			
Manufacturing Process Description	Assembley of Angle & Bracket together.			
Tooling Requirements	Tool(s) Life	None		
	Tool(s) Price	None.		
Manufacturing Operations	**Name**	**Estimating Standard**	**Material Used**	**Wrap rates**
	1 Furnish Parts	—	—	—
	2 Locate & Clamp angle on bracket		/	ASS Rate
	3. Drill & Ream holes (x2)	0.0333/hole	/	— " —
	4 Disassembly & Debur.	0.0333/hole	/	— " —
	5 Locate & hold Clamp on bracket		/	— " —
	6. Drill & Ream holes (x2)	0.0333/hole	/	— " —
	7 Disass & Debur.	0.0333/hole	/	— " —
	8. Dry install 6 rivets (x6)	6	6 Rivets	— " —
	9. Identify ink stamp		/	— " —
Materials Used	**Material Name**		**Material Price**	
	Rivets (x6)		0.06$/5 rivets	
Information Source	Master Plan & BOM & Expert			
Related Processes	Parent	'Rib assembly'		
	Child	'forming (angle)' & 'forming (bracket)'		
Management	Author	[illegible]		
	Date	[redacted]		
	Validation Status	Validated		

Figure C.26 – Manufacturing Process Template for Support Assembly

Risk Sheet

Name:	E.Lavdas
Estimate/Model:	[redacted] Rib Assembly
Date:	[redacted]

#	Risks	Description	Probability	Impact
1	Failure to deliver @ specified intervals	Terms of the contract state that delays of delivery at the specified intervals, incur some financial penalties	Low	Low.
2				

Comments – Action to be taken
For the proposed contract, in general, there aren't any major risks for 2 reasons: 1. There is no development involved; just production and 2. This contract is a continuation of the previous contract; which was exatly the same. Thus there is no learning curve involved, no development of tools/facilities. Only potential risk that experts could identify is failure to deliver product on time (& the corresponding cost penalties incurred).

Figure C.27 – Risk Sheet for the Rib Assembly Cost Estimate

Assumptions Sheet

Assumptions Sheet

This sheet should be used by the estimator, while carrying out the cost estimate, in order to record any assumptions made. This will help keep track of where the estimator gets stuck, and also this document will serve as a record to any of the assumptions present in the cost estimate.

Name:	E. Lavdas
Estimate/Model:	Rib Assembly
Date:	[redacted]

Ass. #	Points where Novice got Stuck	Assumption Made	Question generated (if Applicable)	Expert's Response
1	Not sure how many angles per sheet; do not have exact dimensions	—	How many angles are produced, per Sheet	It will be 19 parts per sheet of Aluminium.
2	↑ Similar for the Brackets	—	How many brackets are produced out of each sheet?	27 Parts/Sheet.
3	Not sure the price of Material for Chromate	Used the same Price for 'Epoxy'	—	That would suffice
4	Process Plans say that it takes 1.53hr to machine the Rib; Not sure if it includes set-up	—	Does the 1.53hr includes the machine set-up?	Yes it does.

Figure C.28 – Rib Assembly Assumptions Sheet (Page 1)

5	—	—	—	Assumption provided by expert: 12 Parts are loaded for each Machine Cycle.
6	Not sure how to estimate the effort for Inspection (QA)	—	What is the time for Inspection per Part?	Use a 7% of the time taken to manufacture the part
7	Process Plans refer to Special Processes (SP); How I estimate effort?	—	How do I estimate the effort for Special Processes?	Add a 10% of the total manufacture time (rule of thumb)
8				
9				
10				
11				

Figure C.29 – Rib Assembly Assumptions Sheet (Page 2)

C.3 Case Study 3 – Airbag Cover Assembly

This Section presents any additional information regarding the Airbag Cover Assembly case study (additionally to what has already been presented in Chapter 8).

The novice acquired a drawing of the airbag cover assembly, presented in Figure C.30. The same drawing was used by the expert in developing his cost estimate.

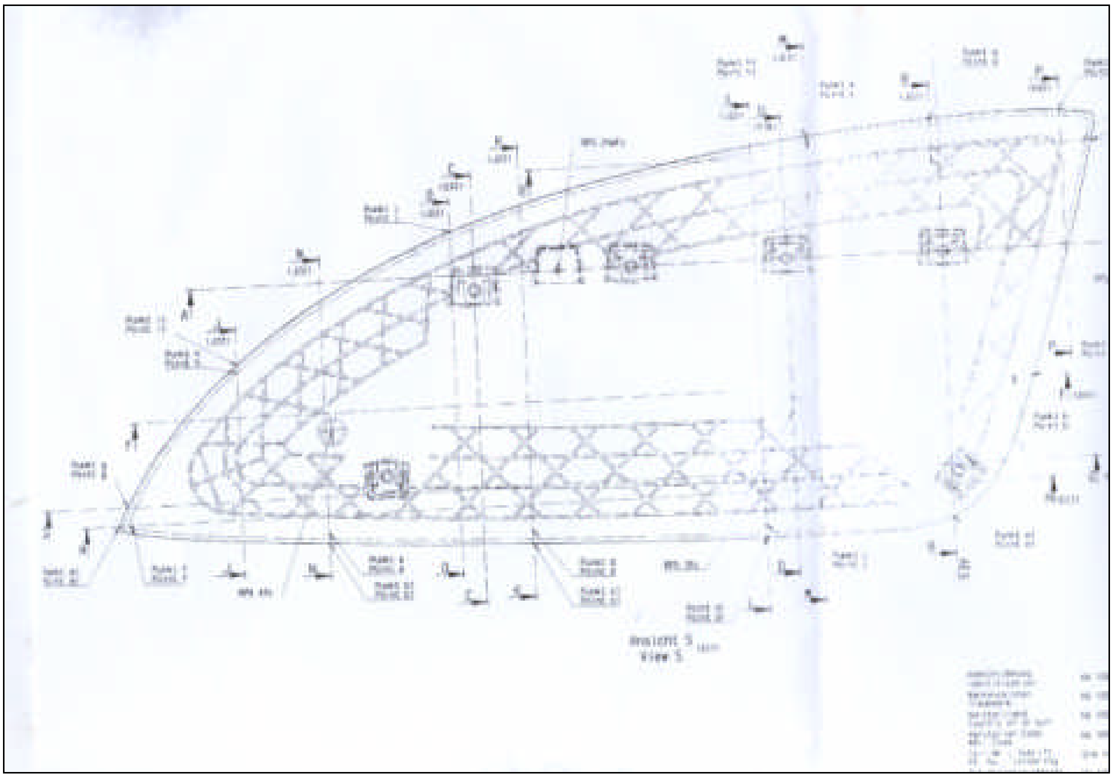


Figure C.30 – Engineering drawing of the Airbag Cover Assembly

C.3.1 Estimate Request

An estimate request was passed over to the novice for producing a should-cost estimate for the production unit cost for the Airbag Cover Assembly. Some of the conditions made explicit within the request are:

- Production Quantity = 50,000 units (throughout 5 years)
- All costs presented in Euros (€), and to be fixed on 2006 economic conditions

Estimate Scope:	Develop a should-cost estimate for the Airbag Cover Assembly based on the assumptions stated within the estimate request. The purpose of the exercise is to check the supplier's quote for this outsourced part.
Production Quantity	50000
Production Rate	10000 units per year
Learning curve	100% (existing contract)
Economic Factors:	
Fiscal Year	2006 to 2010
~~**Selling Costs**~~	~~0%~~
G&A	[redacted]
(Agreed) Profit	[redacted]%

Figure C.31 – Estimate Request for the Airbag Cover Assembly

C.3.2 Templates

This Section presents the templates of the proposed framework, filled in by the author during the course of the case study.

Structural Entity			
Name	Trim Cover Moulding	**P/N**	[redacted]
Type (e.g. Ass., HW)	HW	**Hierarchical Level**	x.x.x.1
Function(s)	see 'Airbag Cover Assembly'		
Description			
Dimensions/Drawing	see Airbag Cover Assembly Drawing.		
In-house or Sub-contracted?			
Method of Manufacture/ Assembly	**Name**	'Trim Cover Moulding'	
	Description	The trim cover is manufactured by injection moulding.	
Information Source			
Related Parts	**Parent**	'Airbag Cover Assembly'	
	Child	—	
Related Operations Characteristics	- 'Trim Cover Moulding'		
Management	**Author**	E.Loudas	
	Date	[redacted]	
	Validation Status	Validated	

Figure C.32 – Structural Entity Template for the Trim Cover Moulding

Structural Entity			
Name	Snap-Nut	P/N	[redacted]
Type (e.g. Ass., HW)	HW	Hierarchical Level	X.X.X.2
Function(s)	To fix the Trim cover secure on the dashboard		
Description			
Dimensions/Drawing	N/A		
In-house or Sub-contracted?	Bought (materials)		
Method of Manufacture/ Assembly	Name	N/A	
	Description	N/A.	
Information Source			
Related Parts	Parent	'Airbag Cover Assembley'	
	Child		
Related Operations Characteristics	—		
Management	Author	E. Lavdas	
	Date	[redacted]	
	Validation Status	Validated	

Figure C.33 – Structural Entity Template for the Snap-Nut

Manufacturing Process				
Name	Injection Moulding			
Manufacturing Process Description	The granules are poured in the machine & they are heated, and injected into the die. After a short cooling period the moulded part is removed from the die.			
Tooling Requirements	**Tool(s) Life**	N/A (already set-up)		
	Tool(s) Price	N/A		
Manufacturing Operations	**Name**	**Estimating Standard**	**Material Used**	**Wrap rates**
	1. Clean Die	0.25 min/part		Moulding labour
	2. Die Closes			
	3. Material Injected	1.25 min/Part	~0.61 kg+	Moulding Machine Rate
	4. Cooling Process	↳ Estimated		
	5. Eject From Die	based on Injection		
	6. Remove From Machine	Moulding Standards		
	7. Trim Excess Material	~0.7 min/part		Moulding labour
	+ weight calculated from available CATIA drawing (including some allowance for scrap material)			
Materials Used	**Material Name**		**Material Price**	
	PC/ABS (Plastic Granules)		~4.54 € /kg	
Information Source	- Expert - Materials Sheet	- Engineering Drawings - Estimating Standards (Available Internet Sources)		
Related Processes	**Parent**	'Trim Cover Assembly'		
	Child	—		
Management	**Author**	G.Loucas		
	Date	[redacted]		
	Validation Status	Validated		

Figure C.34 – Manufacturing Process Template for Injection Moulding

Assumptions Sheet

Assumptions Sheet

This sheet should be used by the estimator, while carrying out the cost estimate, in order to record any assumptions made. This will help keep track of where the estimator gets stuck, and also this document will serve as a record to any of the assumptions present in the cost estimate.

Name:	G Loudas
Estimate/Model:	Airbag Cover Assembly
Date:	[redacted]

Ass. #	Points where Novice got Stuck	Assumption Made	Question generated (if Applicable)	Expert's Response
1	Not sure what the scrap rate is.	3-4% of total material cost?		- The scrap rate should be around 2% of the unit cost (added on unit cost)
2	~~S~~Set-up costs are not included	as previously	Are there any machine set-up costs, and if so how could I calculate them?	Yes there are. You need to multiply the time taken to set-up the machine by the appropriate labour Rate, and then divide this by the batch Quantity (in order to find the set-up cost/part)
3	What do I assume for Parts Inspection?	none	Are there any Inspection Costs?	- Inspection Costs are overheads; so do not need to include them for this task
4				

Figure C.35 – The Assumptions Sheet for the Airbag Cover Assembly Estimate

APPENDIX D – ANALYSIS OF SURVEY RESULTS

Appendix D presents any supplementary material, related to the work presented in Chapters 5 & 6, which was not included within the main body of the thesis.

D.1 Data Analysis & Results of ANOVA Tables

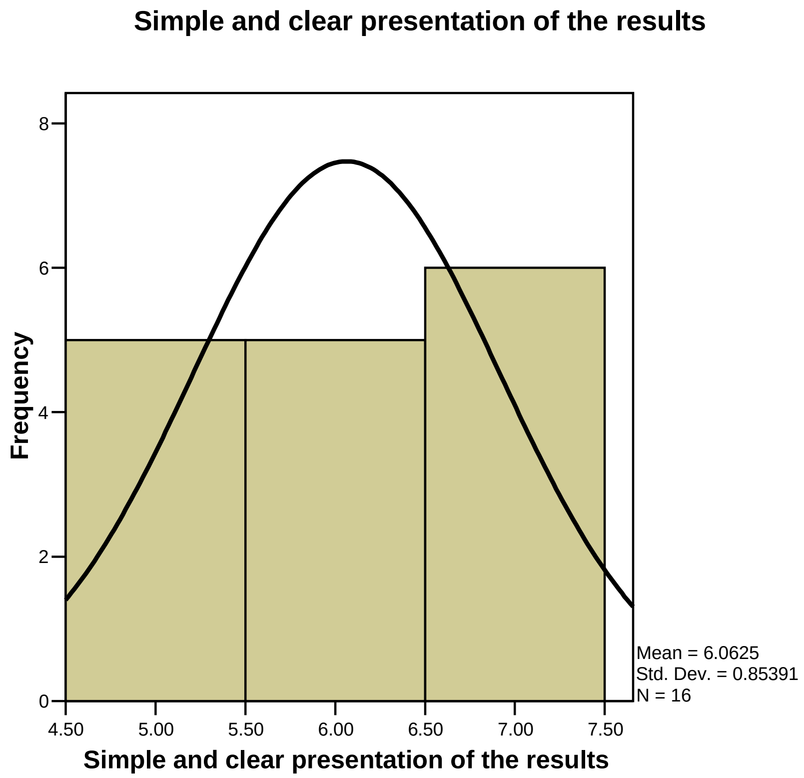
This section presents the quantitative data analysis that the author carried out in order to further scrutinise, and make sense of, the survey results.

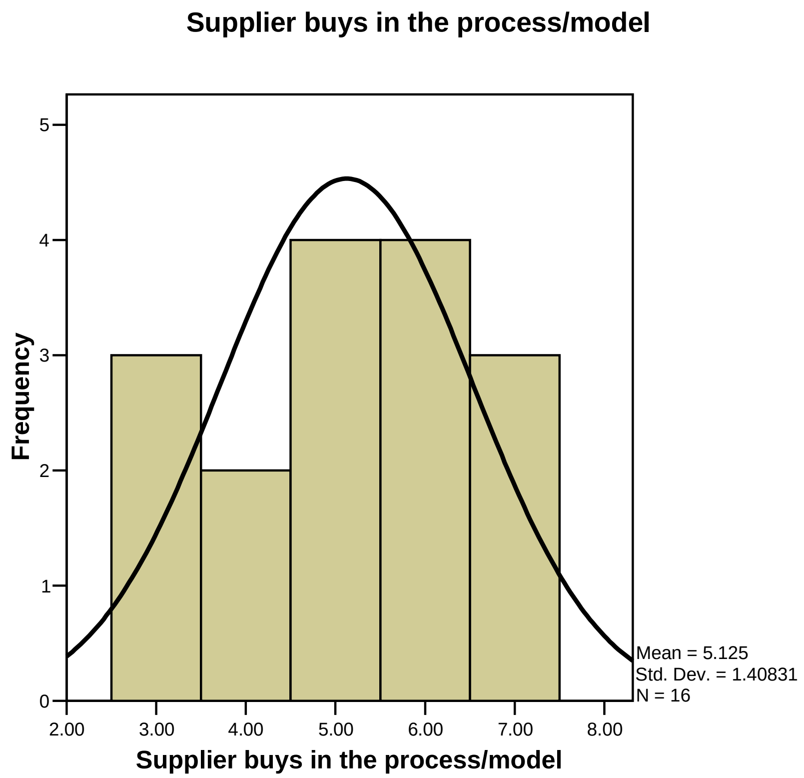
D.1.1 Descriptive Statistics Analysis

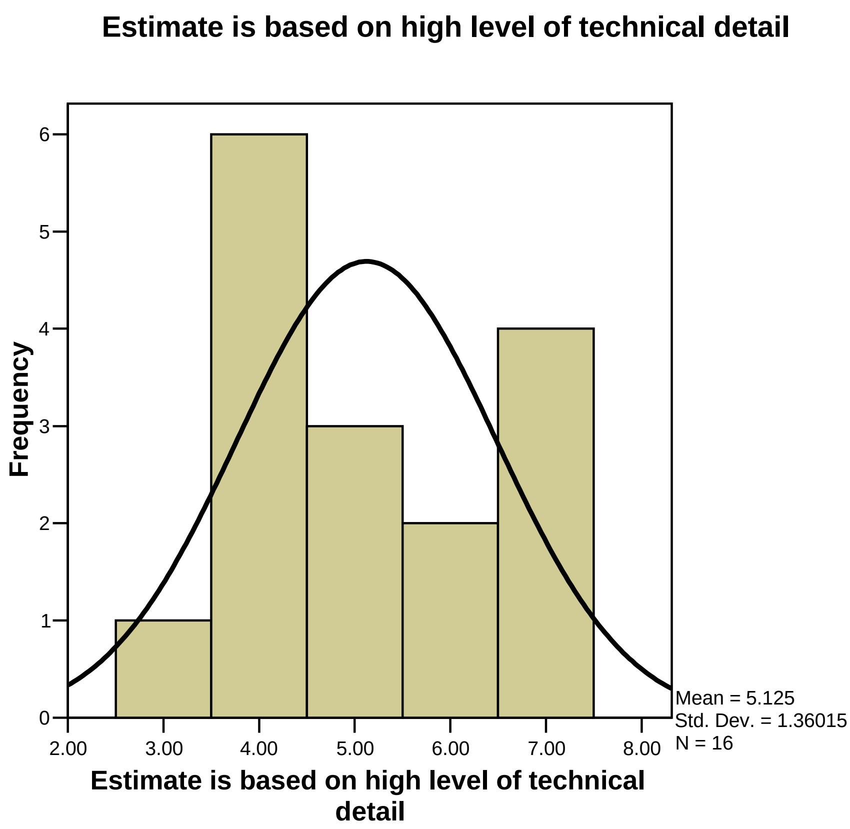
The descriptive analysis of the data from the second stage of the survey is presented in this Section. The initial analysis focused on the calculation of the mean values for all the rating scores of each of the 29 characteristics[*]. Due to the reason that the mean value by itself is not a very representative measure of comparison, the distribution of the ratings for each characteristic was also provided; in the form of histograms. The following Figures exhibit the distribution of the ratings given by the participants against each characteristic.

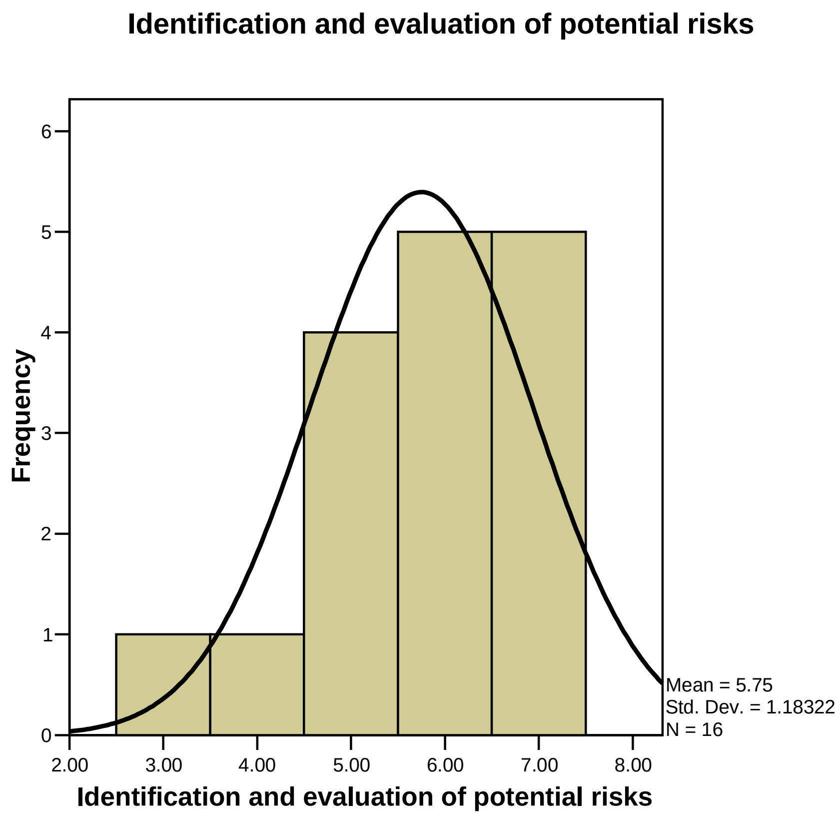
Including a clearly Defined Scope of Work

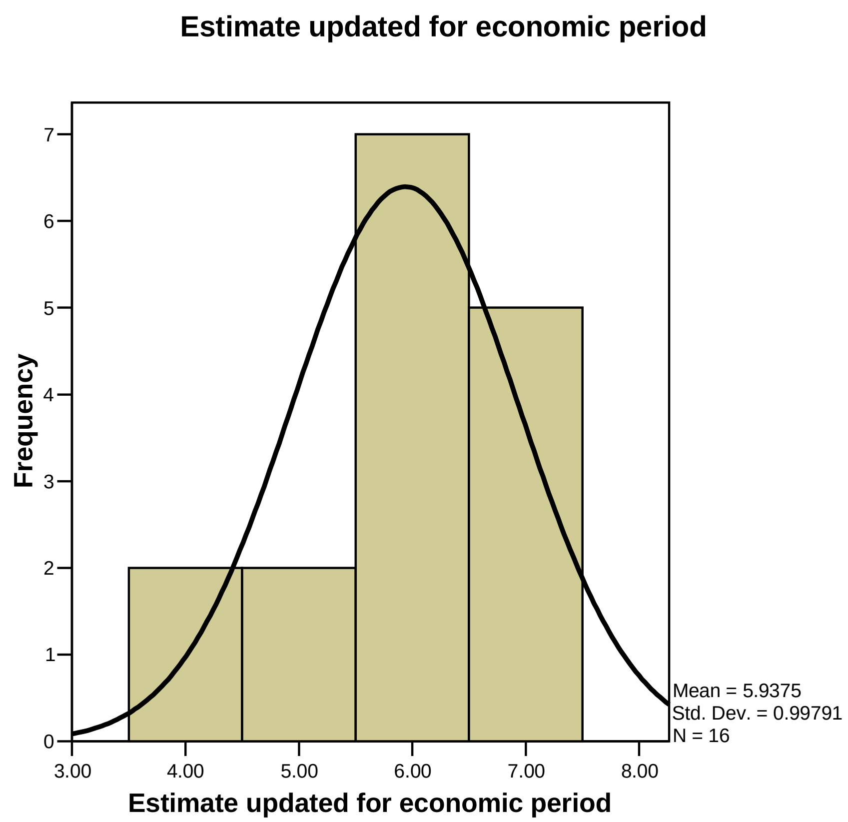
[*] This was before the exclusion of the 'estimate is based on similar to products – use of actuals/historical data' following the results of the correlation analysis. Throughout the statistical analysis all the 29 characteristics were taken into account.

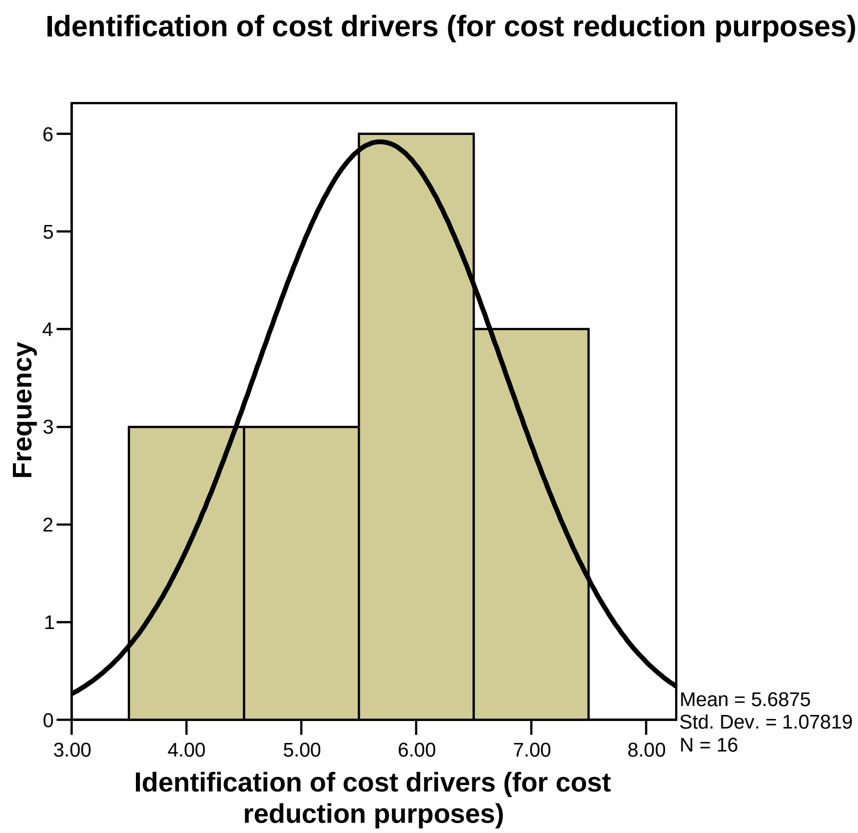

Simple and clear presentation of the results
Frequency
0
2
4
6
8
4.50
5.00
5.50
6.00
6.50
7.00
7.50
Simple and clear presentation of the results
Mean = 6.0625
Std. Dev. = 0.85391
N = 16

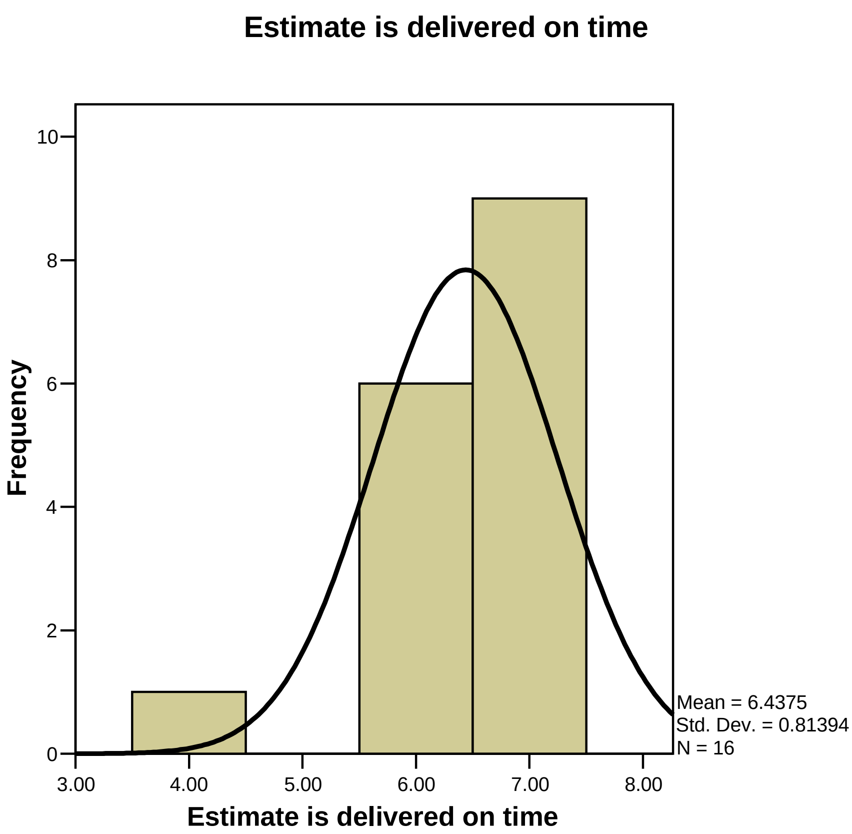

Supplier buys in the process/model
Frequency
0
1
2
3
4
5
2.00
3.00
4.00
5.00
6.00
7.00
8.00
Supplier buys in the process/model
Mean = 5.125
Std. Dev. = 1.40831
N = 16

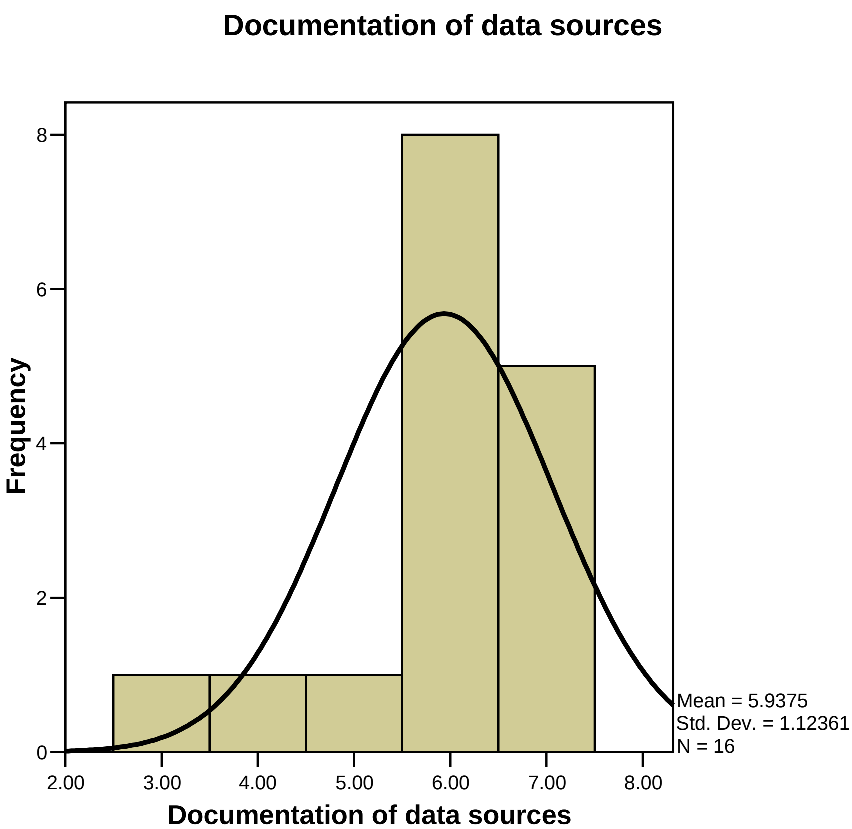

Estimate is based on high level of technical detail
Frequency
0
1
2
3
4
5
6
2.00
3.00
4.00
5.00
6.00
7.00
8.00
Mean = 5.125
Std. Dev. = 1.36015
N = 16
Estimate is based on high level of technical detail

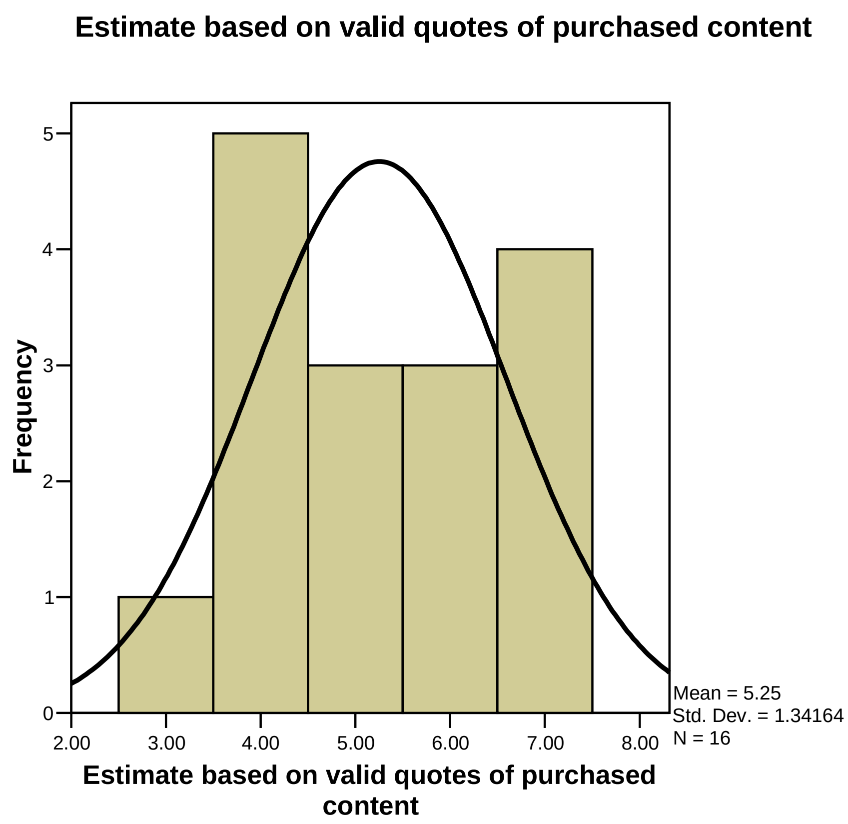

Identification and evaluation of potential risks
Frequency
0
1
2
3
4
5
6
2.00
3.00
4.00
5.00
6.00
7.00
8.00
Mean = 5.75
Std. Dev. = 1.18322
N = 16
Identification and evaluation of potential risks

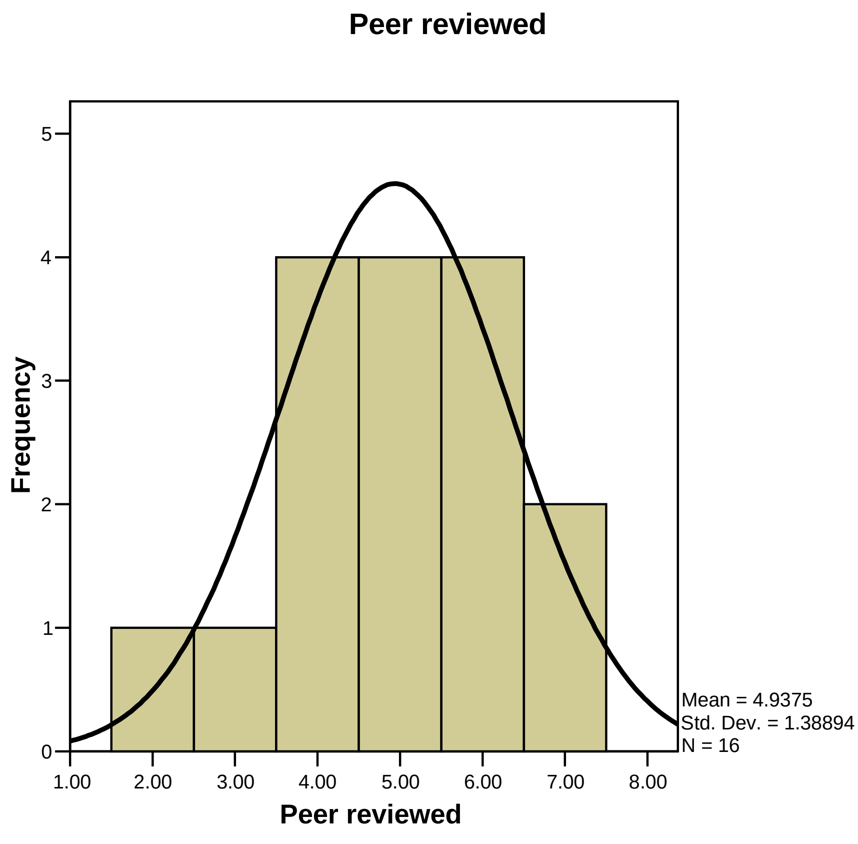

Estimate updated for economic period
Frequency
0
1
2
3
4
5
6
7
3.00
4.00
5.00
6.00
7.00
8.00
Estimate updated for economic period
Mean = 5.9375
Std. Dev. = 0.99791
N = 16


Identification of cost drivers (for cost reduction purposes)
Frequency
0
1
2
3
4
5
6
3.00
4.00
5.00
6.00
7.00
8.00
Identification of cost drivers (for cost reduction purposes)
Mean = 5.6875
Std. Dev. = 1.07819
N = 16

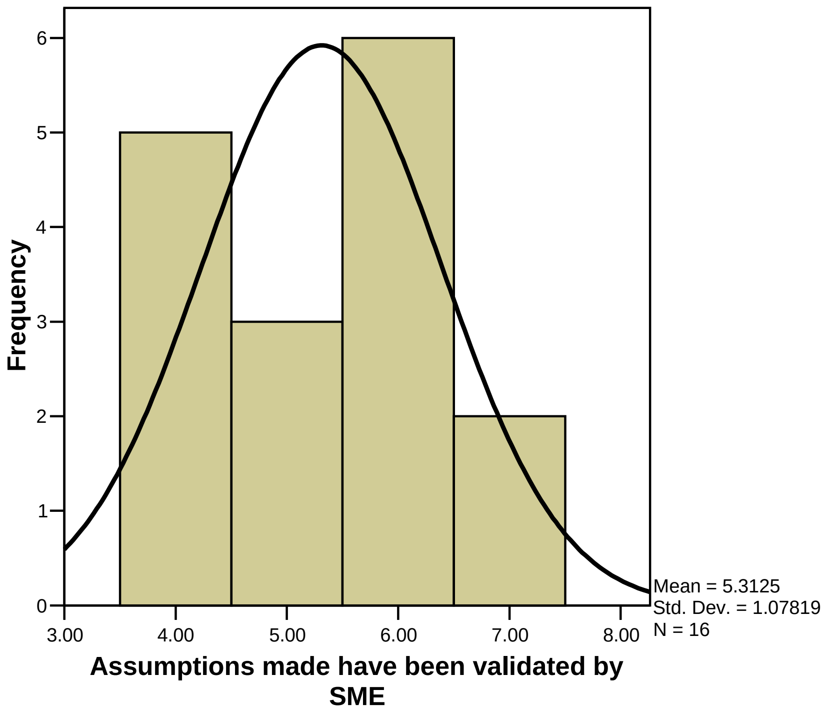

Estimate is delivered on time
Frequency
10
8
6
4
2
0
3.00
4.00
5.00
6.00
7.00
8.00
Estimate is delivered on time
Mean = 6.4375
Std. Dev. = 0.81394
N = 16


Documentation of data sources
Frequency
8
6
4
2
0
2.00
3.00
4.00
5.00
6.00
7.00
8.00
Documentation of data sources
Mean = 5.9375
Std. Dev. = 1.12361
N = 16

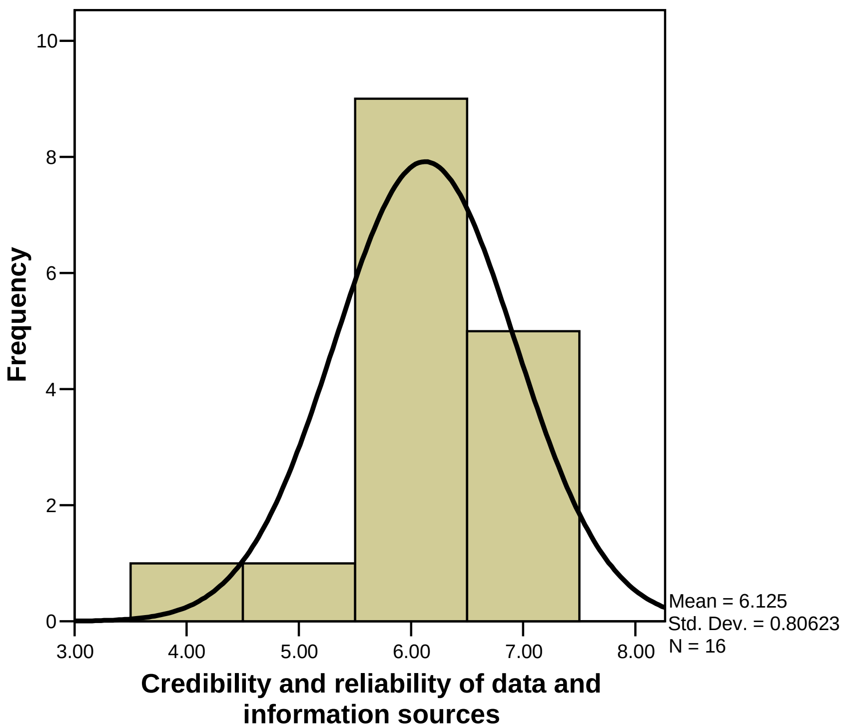

Estimate based on valid quotes of purchased content
Frequency
0
1
2
3
4
5
2.00
3.00
4.00
5.00
6.00
7.00
8.00
Estimate based on valid quotes of purchased content
Mean = 5.25
Std. Dev. = 1.34164
N = 16


Peer reviewed
Frequency
0
1
2
3
4
5
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
Peer reviewed
Mean = 4.9375
Std. Dev. = 1.38894
N = 16

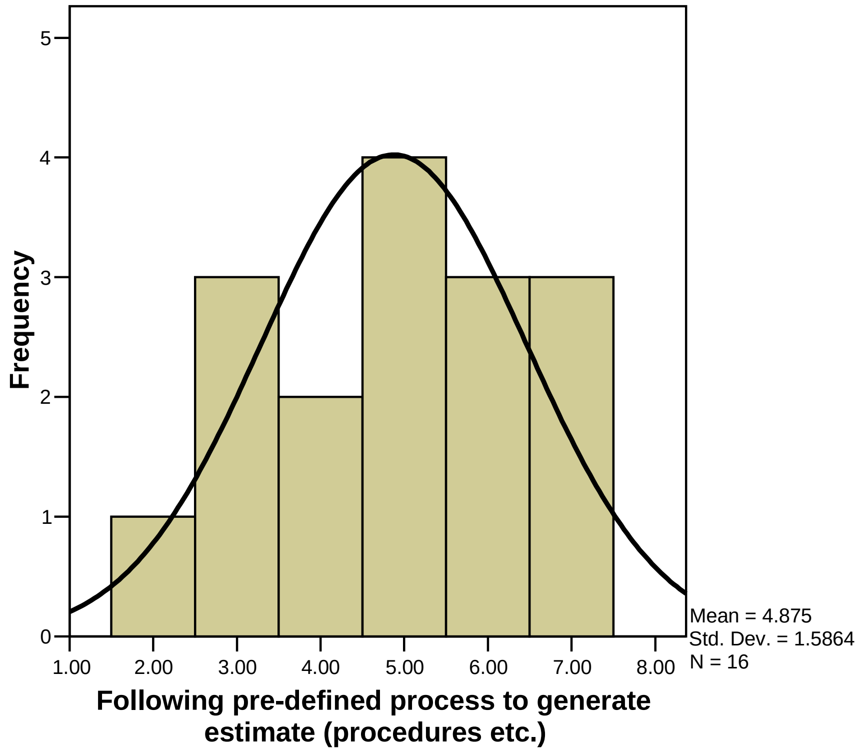
Assumptions made have been validated by SME



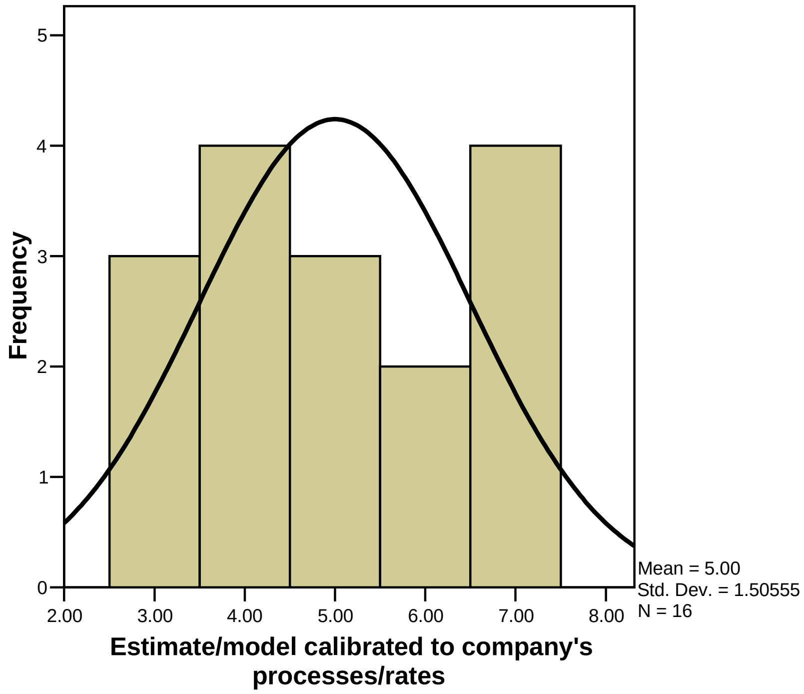
Credibility and reliability of data and information sources

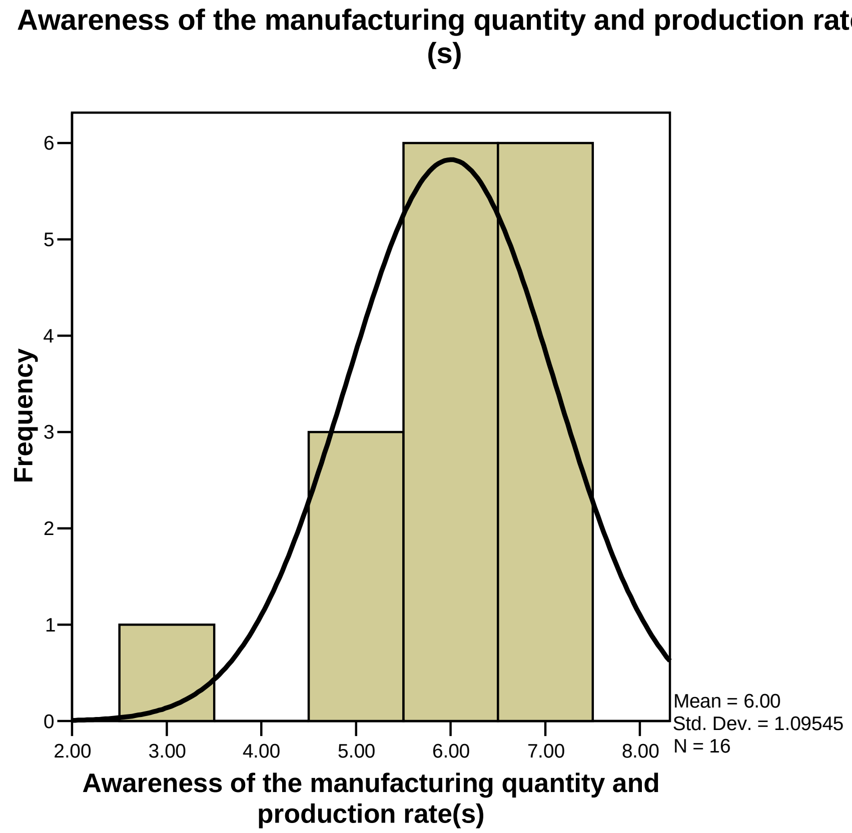


Following pre-defined process to generate estimate (procedures etc.)

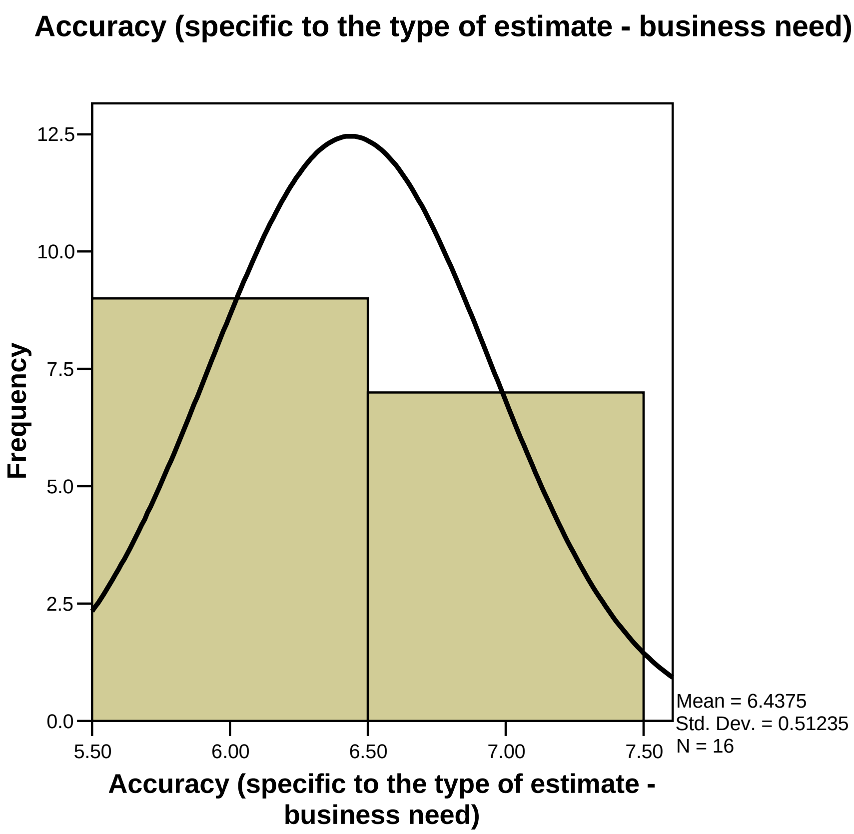


Estimate/model calibrated to company's processes/rates

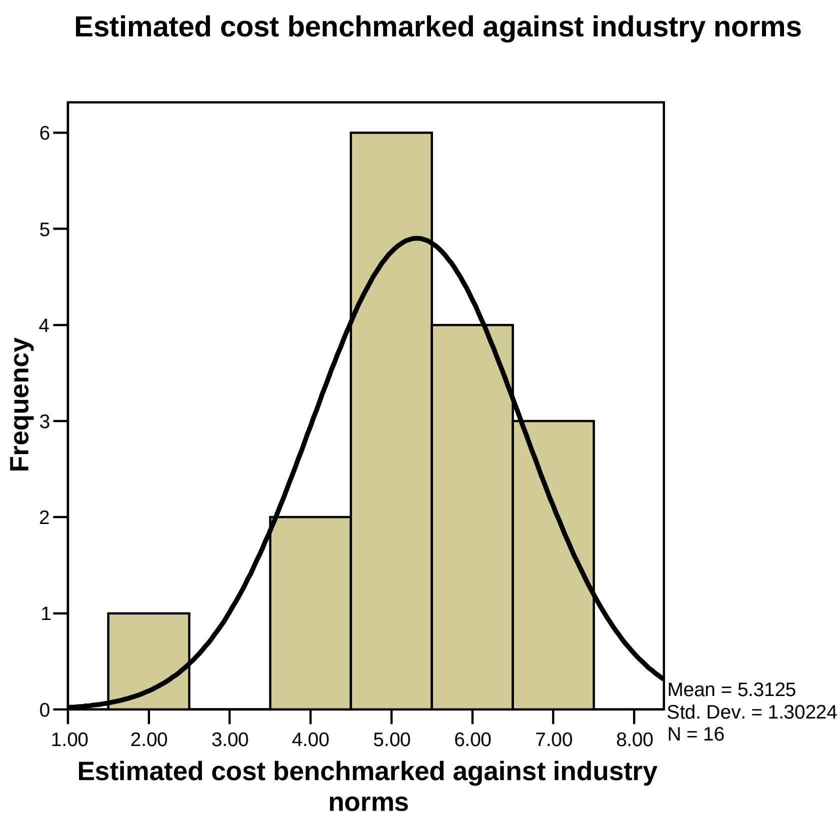


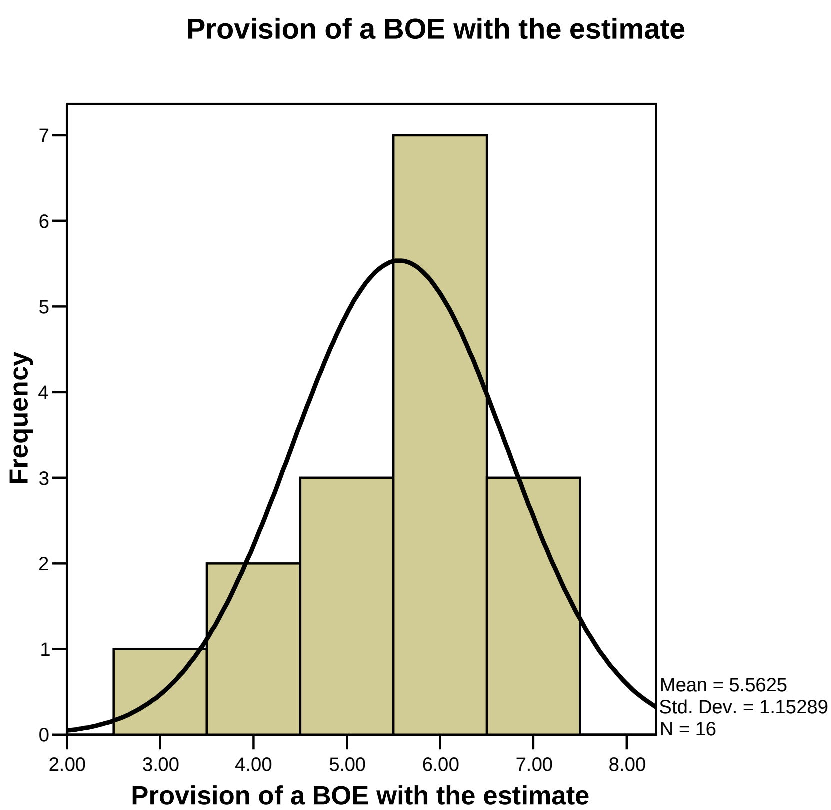


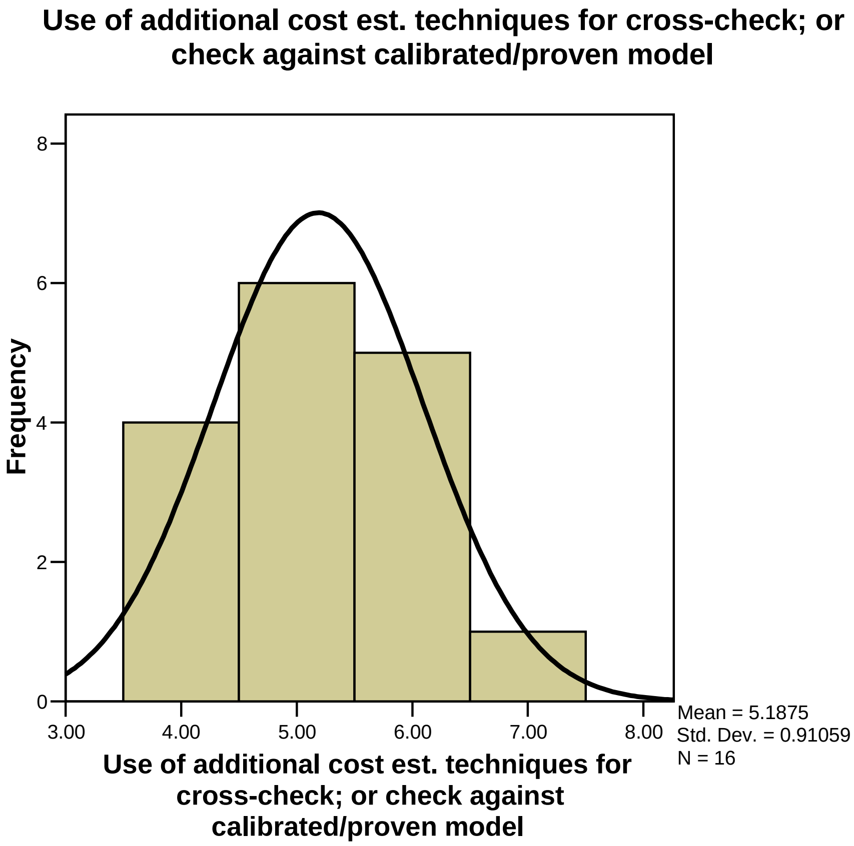
Awareness of the manufacturing quantity and production rate (s)
Frequency
0
1
2
3
4
5
6
2.00
3.00
4.00
5.00
6.00
7.00
8.00
Mean = 6.00
Std. Dev. = 1.09545
N = 16
Awareness of the manufacturing quantity and production rate(s)

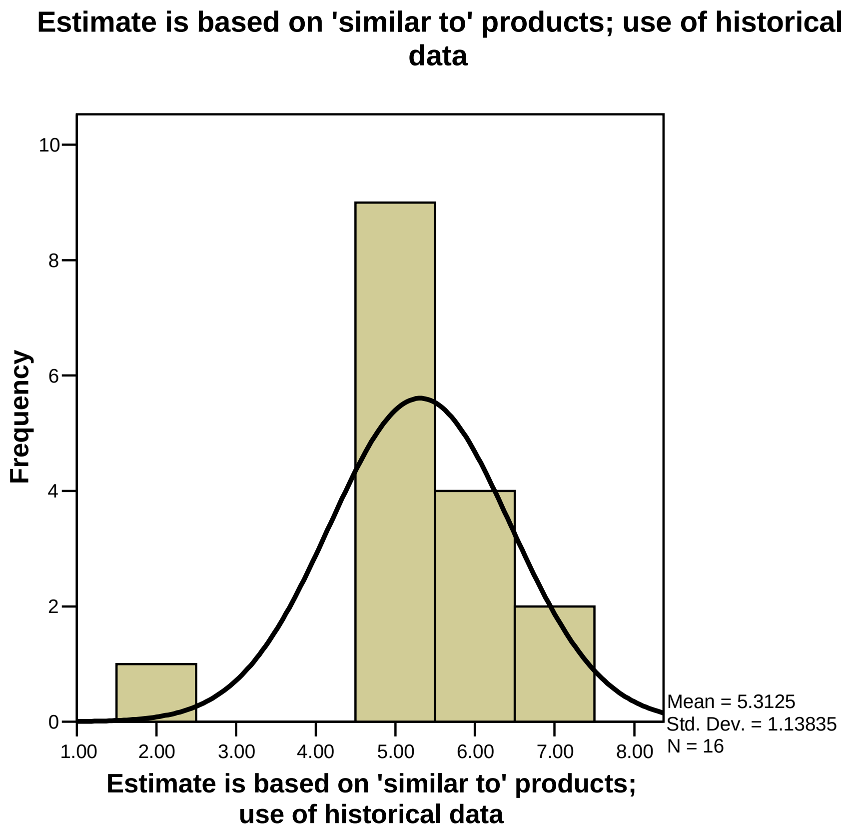


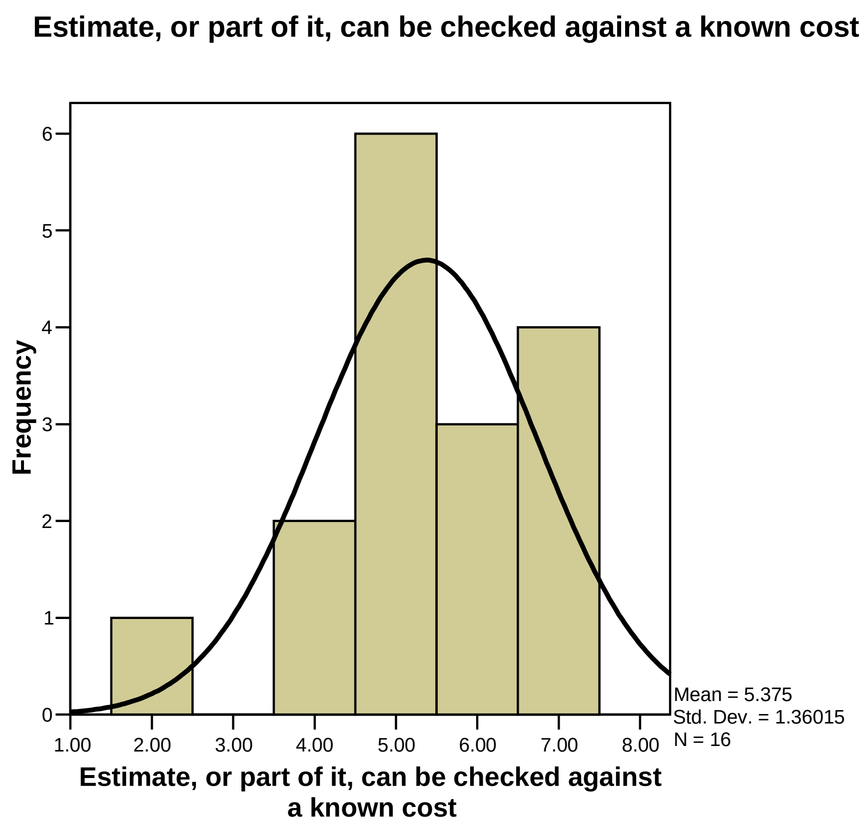
Accuracy (specific to the type of estimate - business need)
Frequency
0.0
2.5
5.0
7.5
10.0
12.5
5.50
6.00
6.50
7.00
7.50
Mean = 6.4375
Std. Dev. = 0.51235
N = 16
Accuracy (specific to the type of estimate - business need)

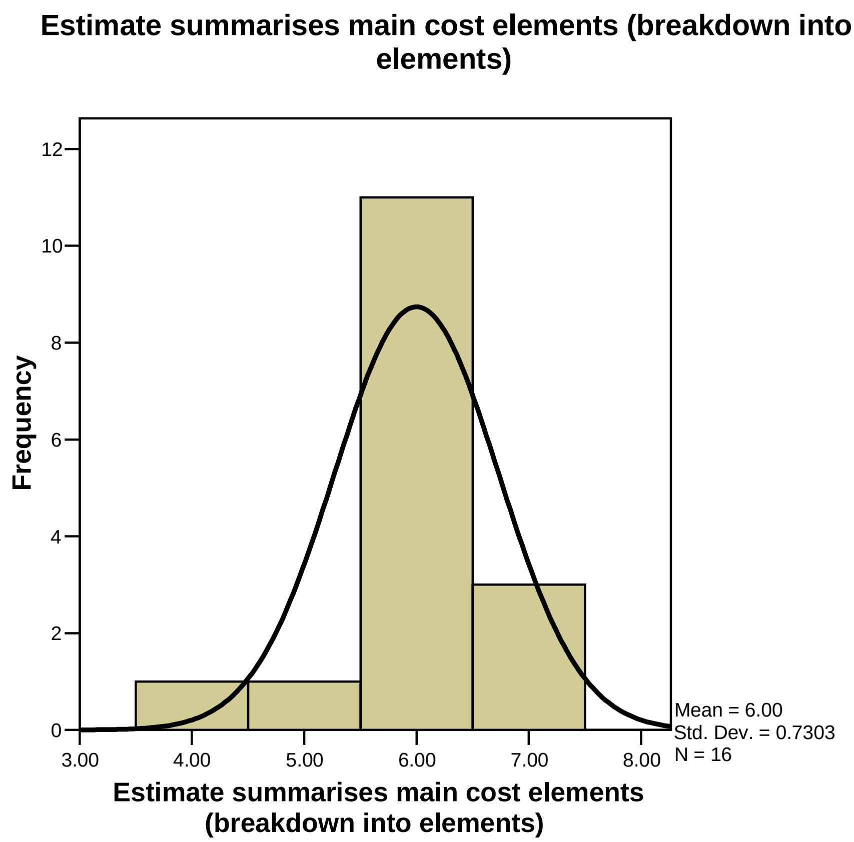

Estimated cost benchmarked against industry norms
Frequency
0
1
2
3
4
5
6
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
Estimated cost benchmarked against industry norms
Mean = 5.3125
Std. Dev. = 1.30224
N = 16

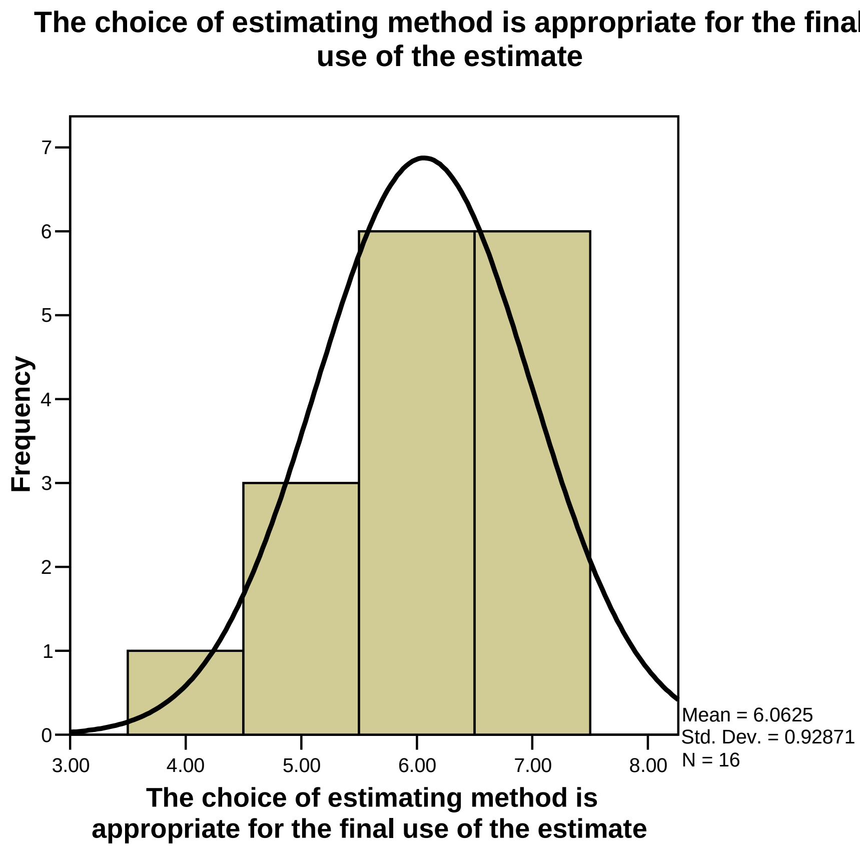

Provision of a BOE with the estimate
Frequency
0
1
2
3
4
5
6
7
2.00
3.00
4.00
5.00
6.00
7.00
8.00
Provision of a BOE with the estimate
Mean = 5.5625
Std. Dev. = 1.15289
N = 16

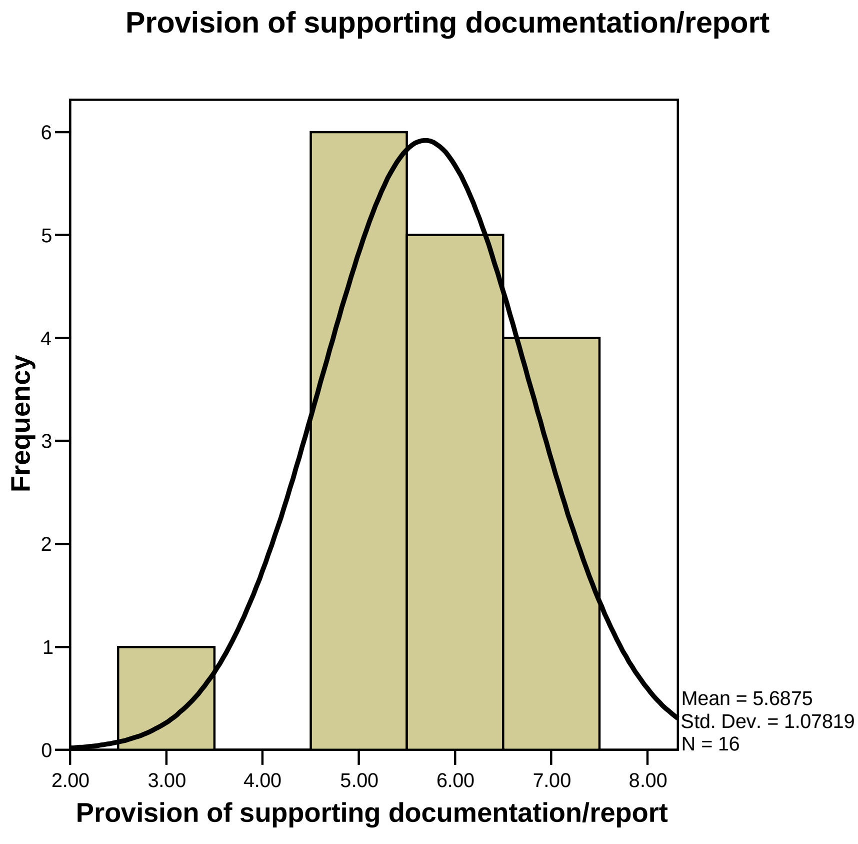

Use of additional cost est. techniques for cross-check; or check against calibrated/proven model
Frequency
0
2
4
6
8
3.00
4.00
5.00
6.00
7.00
8.00
Use of additional cost est. techniques for cross-check; or check against calibrated/proven model
Mean = 5.1875
Std. Dev. = 0.91059
N = 16


Estimate is based on 'similar to' products; use of historical data
Frequency
0
2
4
6
8
10
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
Estimate is based on 'similar to' products; use of historical data
Mean = 5.3125
Std. Dev. = 1.13835
N = 16

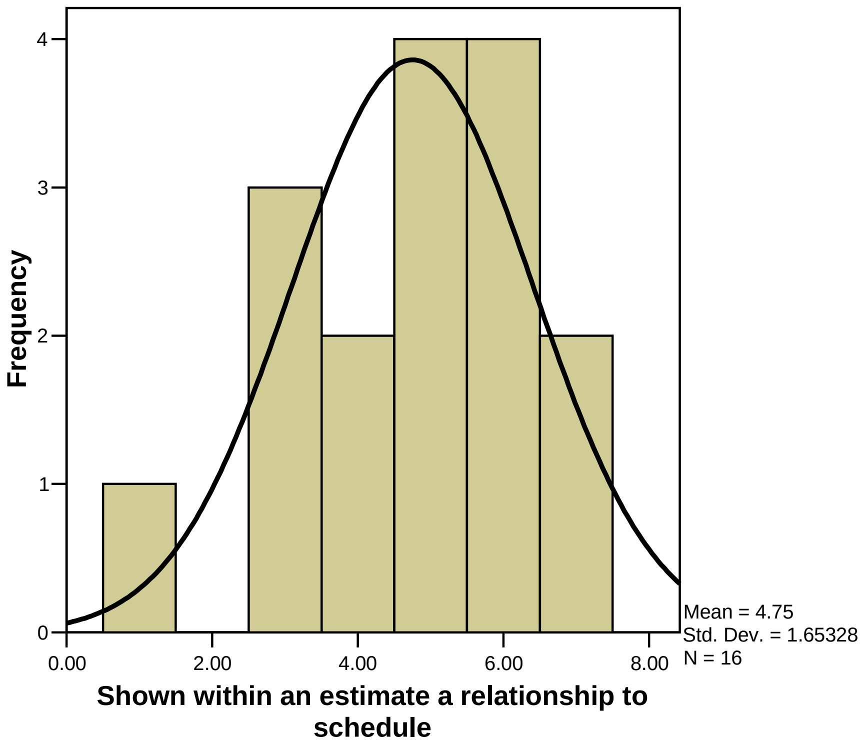

Estimate, or part of it, can be checked against a known cost
Frequency
0
1
2
3
4
5
6
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
Mean = 5.375
Std. Dev. = 1.36015
N = 16
Estimate, or part of it, can be checked against a known cost


Estimate summarises main cost elements (breakdown into elements)
Frequency
0
2
4
6
8
10
12
3.00
4.00
5.00
6.00
7.00
8.00
Mean = 6.00
Std. Dev. = 0.7303
N = 16
Estimate summarises main cost elements (breakdown into elements)

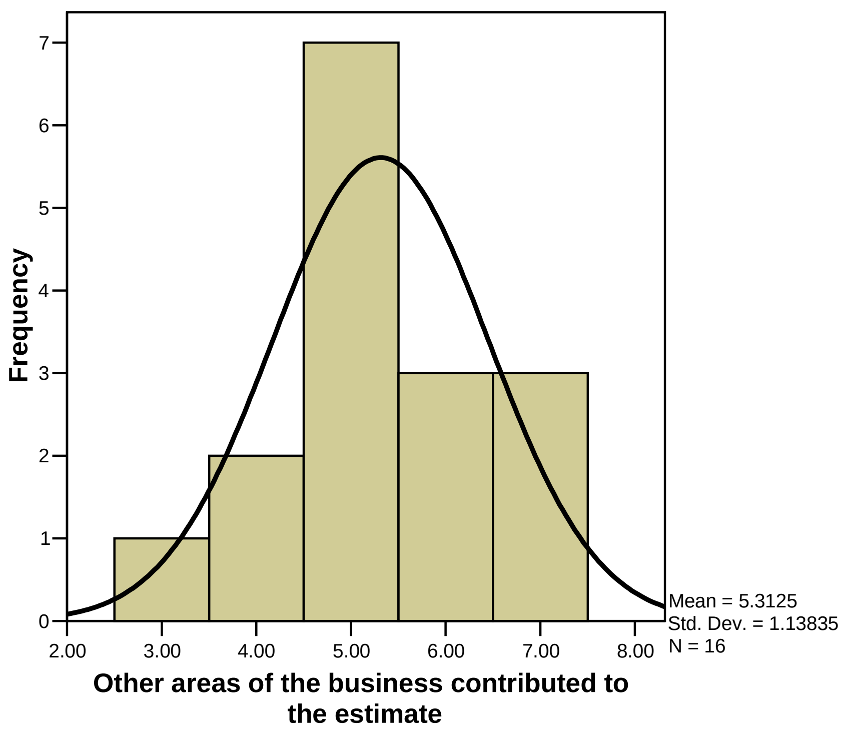

The choice of estimating method is appropriate for the final use of the estimate
Frequency
0
1
2
3
4
5
6
7
3.00
4.00
5.00
6.00
7.00
8.00
The choice of estimating method is appropriate for the final use of the estimate
Mean = 6.0625
Std. Dev. = 0.92871
N = 16

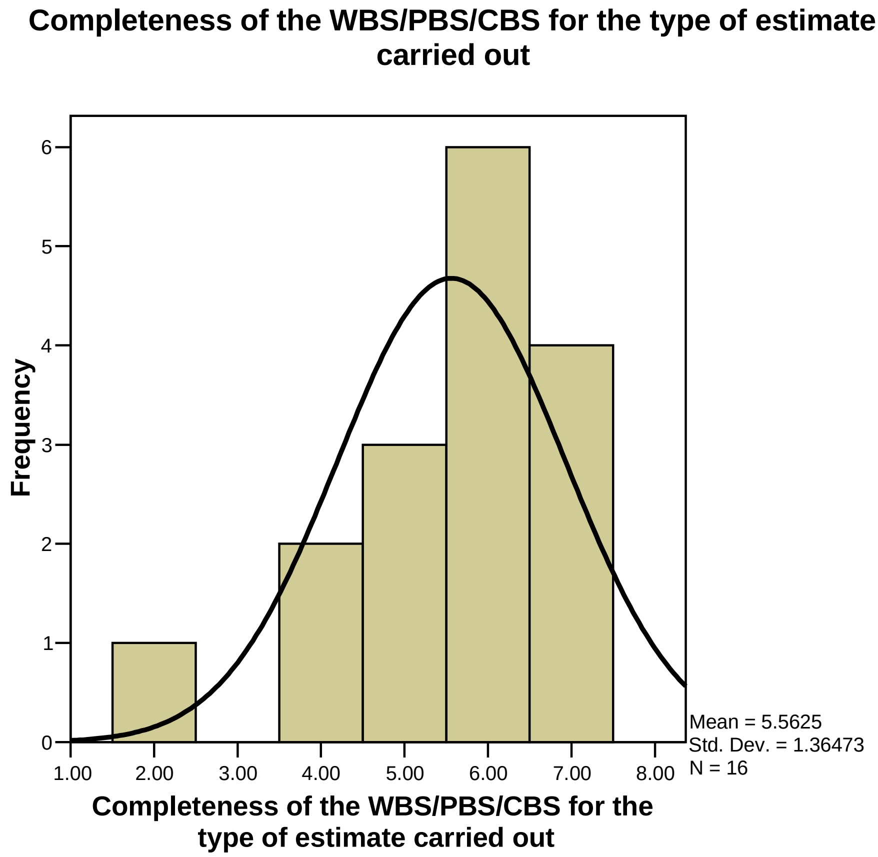

Provision of supporting documentation/report
Frequency
0
1
2
3
4
5
6
2.00
3.00
4.00
5.00
6.00
7.00
8.00
Provision of supporting documentation/report
Mean = 5.6875
Std. Dev. = 1.07819
N = 16

Shown within an estimate a relationship to schedule



Other areas of the business contributed to the estimate





D.1.2 ANOVA Tables

In this Section, the results of the ANOVA tables are presented for each pair of sub-groups, of the overall survey sample. It has to be noted that wherever only 2 sub-groups are compared, the results of the ANOVA are equivalent to a standard t-test.

Based on Industry

		F	Sig.
Documentation of Rules and Assumptions made	Between Groups	9.000	.010
	Within Groups		
	Total		
Including a clearly Defined Scope of Work	Between Groups	.840	.375
	Within Groups		
	Total		
Simple and clear presentation of the results	Between Groups	5.444	.035
	Within Groups		
	Total		
Supplier buys in the process/model	Between Groups	1.145	.303
	Within Groups		
	Total		
Estimate is based on high level of technical detail	Between Groups	.000	1.000
	Within Groups		
	Total		
Identification and evaluation of potential risks	Between Groups	.169	.688
	Within Groups		
	Total		
Estimate updated for economic period	Between Groups	.548	.471
	Within Groups		
	Total		
Identification of cost drivers (for cost reduction purposes)	Between Groups	1.378	.260
	Within Groups		
	Total		
Estimate is delivered on time	Between Groups	.089	.770
	Within Groups		
	Total		
Documentation of data sources	Between Groups	.429	.523
	Within Groups		
	Total		
Estimate based on valid quotes of purchased content	Between Groups	2.435	.141
	Within Groups		
	Total		
Peer reviewed	Between Groups	.799	.386
	Within Groups		
	Total		
Assumptions made have been validated by SME	Between Groups	5.727	.031
	Within Groups		
	Total		
Credibility and reliability of data and information sources	Between Groups	1.600	.227
	Within Groups		
	Total		
Following pre-defined process to generate estimate (procedures etc.)	Between Groups	.887	.362
	Within Groups		
	Total		
Estimate/model calibrated to company's processes/rates	Between Groups	3.153	.098
	Within Groups		
	Total		
Awareness of the manufacturing quantity and production rate(s)	Between Groups	2.000	.179
	Within Groups		
	Total		
Accuracy (specific to the type of estimate - business need)	Between Groups	.226	.642
	Within Groups		
	Total		

		F	Sig.
Estimated cost benchmarked against industry norms	Between Groups	.916	.355
	Within Groups		
	Total		
Provision of a BOE with the estimate	Between Groups	.044	.837
	Within Groups		
	Total		
Use of additional cost est. techniques for cross-check; or check against calibrated/proven	Between Groups	9.610	.008
	Within Groups		
	Total		
Estimate is based on 'similar to' products; use of historical data	Between Groups	1.224	.287
	Within Groups		
	Total		
Estimate, or part of it, can be checked against a known cost	Between Groups	1.235	.285
	Within Groups		
	Total		
Estimate summarises main cost elements (breakdown into elements)	Between Groups	.000	1.000
	Within Groups		
	Total		
The choice of estimating method is appropriate for the final use of the estimate	Between Groups	.068	.798
	Within Groups		
	Total		
Provision of supporting documentation/report	Between Groups	.050	.826
	Within Groups		
	Total		
Shown within an estimate a relationship to schedule	Between Groups	.086	.774
	Within Groups		
	Total		
Other areas of the business contributed to the estimate	Between Groups	.417	.529
	Within Groups		
	Total		
Completeness of the WBS/PBS/CBS for the type of estimate carried out	Between Groups	.031	.862
	Within Groups		
	Total		

Based on Sector

		F	Sig.
Documentation of Rules and Assumptions made	Between Groups Within Groups Total	.564	.465
Including a clearly Defined Scope of Work	Between Groups Within Groups Total	.276	.608
Simple and clear presentation of the results	Between Groups Within Groups Total	.672	.426
Supplier buys in the process/model	Between Groups Within Groups Total	.264	.616
Estimate is based on high level of technical detail	Between Groups Within Groups Total	.058	.814
Identification and evaluation of potential risks	Between Groups Within Groups Total	.310	.587
Estimate updated for economic period	Between Groups Within Groups Total	2.292	.152
Identification of cost drivers (for cost reduction purposes)	Between Groups Within Groups Total	1.722	.211
Estimate is delivered on time	Between Groups Within Groups Total	.276	.608
Documentation of data sources	Between Groups Within Groups Total	1.253	.282
Estimate based on valid quotes of purchased content	Between Groups Within Groups Total	.478	.501
Peer reviewed	Between Groups Within Groups Total	5.546	.034
Assumptions made have been validated by SME	Between Groups Within Groups Total	.045	.835
Credibility and reliability of data and information sources	Between Groups Within Groups Total	2.833	.115
Following pre-defined process to generate estimate (procedures etc.)	Between Groups Within Groups Total	4.514	.052
Estimate/model calibrated to company's processes/rates	Between Groups Within Groups Total	3.810	.071
Awareness of the manufacturing quantity and production rate(s)	Between Groups Within Groups Total	2.383	.145
Accuracy (specific to the type of estimate - business need)	Between Groups Within Groups Total	.718	.411

		F	Sig.
Estimated cost benchmarked against industry norms	Between Groups	.339	.570
	Within Groups		
	Total		
Provision of a BOE with the estimate	Between Groups	.007	.934
	Within Groups		
	Total		
Use of additional cost est. techniques for cross-check; or check against calibrated/proven	Between Groups	.001	.972
	Within Groups		
	Total		
Estimate is based on 'similar to' products; use of historical data	Between Groups	3.008	.105
	Within Groups		
	Total		
Estimate, or part of it, can be checked against a known cost	Between Groups	5.320	.037
	Within Groups		
	Total		
Estimate summarises main cost elements (breakdown into elements)	Between Groups	2.383	.145
	Within Groups		
	Total		
The choice of estimating method is appropriate for the final use of the estimate	Between Groups	.031	.863
	Within Groups		
	Total		
Provision of supporting documentation/report	Between Groups	.074	.789
	Within Groups		
	Total		
Shown within an estimate a relationship to schedule	Between Groups	.006	.938
	Within Groups		
	Total		
Other areas of the business contributed to the estimate	Between Groups	.067	.800
	Within Groups		
	Total		
Completeness of the WBS/PBS/CBS for the type of estimate carried out	Between Groups	.209	.655
	Within Groups		
	Total		

Based on Cost Estimating Technique

		F	Sig.
Documentation of Rules and Assumptions made	Between Groups	.246	.628
	Within Groups		
	Total		
Including a clearly Defined Scope of Work	Between Groups	.322	.580
	Within Groups		
	Total		
Simple and clear presentation of the results	Between Groups	.104	.752
	Within Groups		
	Total		
Supplier buys in the process/model	Between Groups	.002	.966
	Within Groups		
	Total		
Estimate is based on high level of technical detail	Between Groups	10.673	.006
	Within Groups		
	Total		
Identification and evaluation of potential risks	Between Groups	.011	.919
	Within Groups		
	Total		
Estimate updated for economic period	Between Groups	3.852	.070
	Within Groups		
	Total		
Identification of cost drivers (for cost reduction purposes)	Between Groups	.704	.416
	Within Groups		
	Total		
Estimate is delivered on time	Between Groups	.001	.971
	Within Groups		
	Total		
Documentation of data sources	Between Groups	.399	.538
	Within Groups		
	Total		
Estimate based on valid quotes of purchased content	Between Groups	.008	.929
	Within Groups		
	Total		
Peer reviewed	Between Groups	.024	.880
	Within Groups		
	Total		
Assumptions made have been validated by SME	Between Groups	.136	.718
	Within Groups		
	Total		
Credibility and reliability of data and information sources	Between Groups	.006	.941
	Within Groups		
	Total		
Following pre-defined process to generate estimate (procedures etc.)	Between Groups	.001	.970
	Within Groups		
	Total		
Estimate/model calibrated to company's processes/rates	Between Groups	.105	.750
	Within Groups		
	Total		
Awareness of the manufacturing quantity and production rate(s)	Between Groups	.200	.661
	Within Groups		
	Total		
Accuracy (specific to the type of estimate - business need)	Between Groups	.004	.953
	Within Groups		
	Total		

		F	Sig.
Estimated cost benchmarked against industry norms	Between Groups	.005	.945
	Within Groups		
	Total		
Provision of a BOE with the estimate	Between Groups	1.900	.190
	Within Groups		
	Total		
Use of additional cost est. techniques for cross-check; or check against calibrated/proven	Between Groups	.136	.717
	Within Groups		
	Total		
Estimate is based on 'similar to' products; use of historical data	Between Groups	.263	.616
	Within Groups		
	Total		
Estimate, or part of it, can be checked against a known cost	Between Groups	.018	.895
	Within Groups		
	Total		
Estimate summarises main cost elements (breakdown into elements)	Between Groups	.459	.509
	Within Groups		
	Total		
The choice of estimating method is appropriate for the final use of the estimate	Between Groups	9.674	.008
	Within Groups		
	Total		
Provision of supporting documentation/report	Between Groups	1.049	.323
	Within Groups		
	Total		
Shown within an estimate a relationship to schedule	Between Groups	1.336	.267
	Within Groups		
	Total		
Other areas of the business contributed to the estimate	Between Groups	.263	.616
	Within Groups		
	Total		
Completeness of the WBS/PBS/CBS for the type of estimate carried out	Between Groups	.495	.493
	Within Groups		
	Total		

Based on Position

		F	Sig.
Documentation of Rules and Assumptions made	Between Groups Within Groups Total	.829	.378
Including a clearly Defined Scope of Work	Between Groups Within Groups Total	1.099	.312
Simple and clear presentation of the results	Between Groups Within Groups Total	.991	.336
Supplier buys in the process/model	Between Groups Within Groups Total	3.563	.080
Estimate is based on high level of technical detail	Between Groups Within Groups Total	1.629	.223
Identification and evaluation of potential risks	Between Groups Within Groups Total	.096	.761
Estimate updated for economic period	Between Groups Within Groups Total	.712	.413
Identification of cost drivers (for cost reduction purposes)	Between Groups Within Groups Total	.925	.353
Estimate is delivered on time	Between Groups Within Groups Total	.645	.435
Documentation of data sources	Between Groups Within Groups Total	.556	.468
Estimate based on valid quotes of purchased content	Between Groups Within Groups Total	.700	.417
Peer reviewed	Between Groups Within Groups Total	.004	.949
Assumptions made have been validated by SME	Between Groups Within Groups Total	1.326	.269
Credibility and reliability of data and information sources	Between Groups Within Groups Total	.477	.501
Following pre-defined process to generate estimate (procedures etc.)	Between Groups Within Groups Total	.339	.570
Estimate/model calibrated to company's processes/rates	Between Groups Within Groups Total	.000	1.000
Awareness of the manufacturing quantity and production rate(s)	Between Groups Within Groups Total	2.036	.175
Accuracy (specific to the type of estimate - business need)	Between Groups Within Groups Total	1.750	.207

		F	Sig.
Estimated cost benchmarked against industry norms	Between Groups	.883	.363
	Within Groups		
	Total		
Provision of a BOE with the estimate	Between Groups	1.569	.231
	Within Groups		
	Total		
Use of additional cost est. techniques for cross-check; or check against calibrated/proven	Between Groups	1.933	.186
	Within Groups		
	Total		
Estimate is based on 'similar to' products; use of historical data	Between Groups	.058	.813
	Within Groups		
	Total		
Estimate, or part of it, can be checked against a known cost	Between Groups	.465	.506
	Within Groups		
	Total		
Estimate summarises main cost elements (breakdown into elements)	Between Groups	25.200	.000
	Within Groups		
	Total		
The choice of estimating method is appropriate for the final use of the estimate	Between Groups	.490	.495
	Within Groups		
	Total		
Provision of supporting documentation/report	Between Groups	.182	.677
	Within Groups		
	Total		
Shown within an estimate a relationship to schedule	Between Groups	.049	.828
	Within Groups		
	Total		
Other areas of the business contributed to the estimate	Between Groups	.058	.813
	Within Groups		
	Total		
Completeness of the WBS/PBS/CBS for the type of estimate carried out	Between Groups	2.848	.114
	Within Groups		
	Total		

Based on Experience

		F	Sig.
Documentation of Rules and Assumptions made	Between Groups	.452	.721
	Within Groups		
	Total		
Including a clearly Defined Scope of Work	Between Groups	.818	.508
	Within Groups		
	Total		
Simple and clear presentation of the results	Between Groups	.375	.773
	Within Groups		
	Total		
Supplier buys in the process/model	Between Groups	3.323	.057
	Within Groups		
	Total		
Estimate is based on high level of technical detail	Between Groups	2.167	.145
	Within Groups		
	Total		
Identification and evaluation of potential risks	Between Groups	.441	.728
	Within Groups		
	Total		
Estimate updated for economic period	Between Groups	1.558	.251
	Within Groups		
	Total		
Identification of cost drivers (for cost reduction purposes)	Between Groups	.337	.799
	Within Groups		
	Total		
Estimate is delivered on time	Between Groups	2.534	.106
	Within Groups		
	Total		
Documentation of data sources	Between Groups	.940	.452
	Within Groups		
	Total		
Estimate based on valid quotes of purchased content	Between Groups	1.562	.250
	Within Groups		
	Total		
Peer reviewed	Between Groups	.677	.583
	Within Groups		
	Total		
Assumptions made have been validated by SME	Between Groups	2.861	.081
	Within Groups		
	Total		
Credibility and reliability of data and information sources	Between Groups	1.639	.233
	Within Groups		
	Total		
Following pre-defined process to generate estimate (procedures etc.)	Between Groups	.819	.508
	Within Groups		
	Total		
Estimate/model calibrated to company's processes/rates	Between Groups	.496	.692
	Within Groups		
	Total		
Awareness of the manufacturing quantity and production rate(s)	Between Groups	2.595	.101
	Within Groups		
	Total		
Accuracy (specific to the type of estimate - business need)	Between Groups	6.500	.007
	Within Groups		
	Total		

		F	Sig.
Estimated cost benchmarked against industry norms	Between Groups	.660	.592
	Within Groups		
	Total		
Provision of a BOE with the estimate	Between Groups	.785	.525
	Within Groups		
	Total		
Use of additional cost est. techniques for cross-check; or check	Between Groups	.523	.675
	Within Groups		
	Total		
Estimate is based on 'similar to' products; use of historical data	Between Groups	.004	1.000
	Within Groups		
	Total		
Estimate, or part of it, can be checked against a known cost	Between Groups	.339	.798
	Within Groups		
	Total		
Estimate summarises main cost elements (breakdown into elements)	Between Groups	1.647	.231
	Within Groups		
	Total		
The choice of estimating method is appropriate for the final use of the	Between Groups	.705	.567
	Within Groups		
	Total		
Provision of supporting documentation/report	Between Groups	2.975	.074
	Within Groups		
	Total		
Shown within an estimate a relationship to schedule	Between Groups	.091	.963
	Within Groups		
	Total		
Other areas of the business contributed to the estimate	Between Groups	.785	.525
	Within Groups		
	Total		
Completeness of the WBS/PBS/CBS for the type of estimate carried	Between Groups	.640	.604
	Within Groups		
	Total		

D.2 Correlation Matrix – Analysis of Dependent Variables

A number of survey participants felt that two characteristics from the proposed 29 had a similar meaning. The author wanted to identify whether this is just the view of these particular respondents, or whether these characteristics are indeed similar. The correlation coefficient of each characteristic, to each other, was calculated in order to identify any correlation in the participants' rating scores.

D.2.1 Correlation Matrix Results

The statistical software SPSS was used to generate a correlation matrix, exhibited in Figure D.1. The correlation coefficient shown in the table, for each pair of characteristics, can range from -1 to 1. The closer the coefficient value is to 0, it means that there is not any correlation present between two characteristics. A positive value signifies the existence of correlation (in terms of similarity), while a negative value signifies the existence of negative correlation (dissimilarity). Values of

+/- 0.9 and higher (towards +1 and -1, correspondingly), would exhibit a very strong correlation between two factors.

In Figure D.1, the names of the characteristics were substituted with numerical identifiers. The results of the analysis of the correlation matrix, were presented in Section 5.3.5.

Inter-item Correlation Matrix

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
1	1.000	.215	.426	.516	-.099	.046	.175	.212	.480	-.036	.201	.281	.087	.234	.153	.215	.197	.131	.238	-.152	.724	.461	.495	.000	-.188	-.087	-.098	-.012	.10
2	.215	1.000	.054	.182	.008	.467	.446	.394	-.208	.542	.443	.498	.593	.724	.252	.272	.224	.310	.051	.502	.332	.130	.203	-.112	-.127	.698	.285	.562	.42
3	.426	.054	1.000	.492	.280	-.049	.240	.095	.246	-.274	.393	.004	.267	-.012	-.092	.156	.214	.390	.041	-.106	.498	.184	.036	.000	-.173	-.122	.153	-.159	-.49
4	.516	.182	.492	1.000	.061	.220	.148	.335	.589	-.037	.159	.311	.368	.220	-.112	.094	.562	.289	.232	-.293	.344	.140	.113	.519	-.363	.159	-.100	.140	-.07
5	-.099	.008	.280	.061	1.000	.062	.546	.483	.128	-.038	.566	.146	.290	.167	.224	.163	.224	.586	.089	-.048	-.020	.274	.153	.268	-.587	.028	.222	.188	.06
6	.046	.467	-.049	.220	.062	1.000	.268	.562	.052	.439	.378	.720	.170	.524	.479	.374	.566	.192	.400	.550	.170	.359	.476	.077	.076	.666	.511	.705	.50
7	.175	.446	.240	.148	.546	.268	1.000	.476	.118	.294	.261	.286	.515	.508	.163	.222	.183	.318	.016	.148	.454	.077	.117	-.183	-.427	.414	.030	.370	.37
8	.212	.394	.095	.335	.483	.562	.476	1.000	.014	.203	.518	.654	.491	.585	.365	.370	.734	.264	.549	.151	.335	.519	.585	.339	-.445	.427	.365	.465	.39
9	.480	-.208	.246	.589	.128	.052	.118	.014	1.000	.105	.015	.262	.062	.114	.200	.218	.224	.470	-.012	-.138	.152	.058	.203	.336	-.127	.090	-.161	.058	.06
10	-.036	.542	-.274	-.037	-.038	.439	.294	.203	.105	1.000	.144	.595	.512	.745	.669	.591	.217	.282	-.168	.595	.012	-.140	.104	.000	.068	.753	.027	.329	.54
11	.201	.443	.393	.159	.566	.378	.261	.518	.015	.144	1.000	.438	.495	.339	.423	.396	.454	.703	.410	.420	.177	.513	.420	.272	-.067	.334	.751	.469	.10
12	.281	.498	.004	.311	.146	.720	.286	.654	.262	.595	.438	1.000	.459	.841	.813	.829	.657	.416	.233	.565	.273	.435	.613	.263	-.048	.654	.370	.561	.44
13	.087	.593	.267	.368	.290	.170	.515	.491	.062	.512	.495	.459	1.000	.642	.297	.493	.452	.460	.163	.332	.208	-.031	.006	.339	-.221	.606	.196	.404	.19
14	.234	.724	-.012	.220	.167	.524	.508	.585	.114	.745	.339	.841	.642	1.000	.691	.714	.528	.343	.087	.493	.420	.318	.502	.000	-.278	.738	.125	.463	.59
15	.153	.252	-.092	-.112	.224	.479	.163	.365	.200	.669	.423	.813	.297	.691	1.000	.893	.345	.400	.085	.624	.110	.392	.548	.115	.051	.443	.292	.355	.43
16	.215	.272	.156	.094	.163	.374	.222	.370	.218	.591	.396	.829	.493	.714	.893	1.000	.445	.432	.034	.538	.243	.311	.423	.182	.095	.411	.241	.233	.16
17	.197	.224	.214	.562	.224	.566	.183	.734	.224	.217	.454	.657	.452	.528	.345	.445	1.000	.238	.561	.106	.401	.535	.582	.333	-.197	.452	.368	.267	.26
18	.131	.310	.390	.289	.586	.192	.318	.264	.470	.282	.703	.416	.460	.343	.400	.432	.238	1.000	-.119	.346	-.045	.093	.132	.356	-.061	.385	.453	.321	-.08
19	.238	.051	.041	.232	.089	.400	.016	.549	-.012	-.168	.410	.233	.163	.087	.085	.034	.561	-.119	1.000	-.080	.341	.694	.607	.280	-.127	.027	.317	.379	.38
20	-.152	.502	-.106	-.293	-.048	.550	.148	.151	-.138	.595	.420	.565	.332	.493	.624	.538	.106	.346	-.080	1.000	-.107	-.041	.154	-.158	.463	.741	.673	.619	.29
21	.724	.332	.498	.344	-.020	.170	.454	.335	.152	.012	.177	.273	.208	.420	.110	.243	.401	-.045	.341	-.107	1.000	.583	.585	-.401	-.251	.064	-.055	-.060	.23
22	.461	.130	.184	.140	.274	.359	.077	.519	.058	-.140	.513	.435	-.031	.318	.392	.311	.535	.093	.694	-.041	.583	1.000	.910	.000	-.272	-.078	.292	.177	.35
23	.495	.203	.036	.113	.153	.476	.117	.585	.203	.104	.420	.613	.006	.502	.548	.423	.582	.132	.607	.154	.585	.910	1.000	-.067	-.178	.176	.311	.264	.52
24	.000	-.112	.000	.519	.268	.077	-.183	.339	.336	.000	.272	.263	.339	.000	.115	.182	.333	.356	.280	-.158	-.401	.000	-.067	1.000	-.197	.000	.055	.241	-.13
25	-.188	-.127	-.173	-.363	-.587	.076	-.427	-.445	-.127	.068	-.067	-.048	-.221	-.278	.051	.095	-.197	-.061	-.127	.463	-.251	-.272	-.178	-.197	1.000	.087	.402	-.020	-.29
26	-.087	.698	-.122	.159	.028	.666	.414	.427	.090	.753	.334	.654	.606	.738	.443	.411	.452	.385	.027	.741	.064	-.078	.176	.000	.087	1.000	.439	.682	.53
27	-.098	.285	.153	-.100	.222	.511	.030	.365	-.161	.027	.751	.370	.196	.125	.292	.241	.368	.453	.317	.673	-.055	.292	.311	.055	.402	.439	1.000	.540	.00
28	-.012	.562	-.159	.140	.188	.705	.370	.465	.058	.329	.469	.561	.404	.463	.355	.233	.267	.321	.379	.619	-.060	.177	.264	.241	-.020	.682	.540	1.000	.56
29	.108	.424	-.490	-.074	.067	.506	.370	.399	.064	.546	.100	.442	.190	.598	.435	.162	.268	-.089	.382	.294	.231	.351	.525	-.134	-.293	.535	.007	.566	1.00

Figure D.1 – Correlation Analysis Results

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APPENDIX E – CEQA TOOL USER MANUAL

C.1 User Manual

In this Section, a copy of the CEQA tool user manual is presented. Its purpose is to familiarise users with the tool, as well as to provide further explanations regarding the characteristics' rating process.

CEQA Tool User Manual

Author: Evaggelos Lavdas

Contents

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- European Space Agency
- Eaton Aerospace
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- BAE Systems
- Whessoe Oil & Gas
- L-3 Communications
- MITRE Corporation
- Rolls-Royce
- PRICE Systems
- Caterpillar Defence Products
- British Nuclear Group
- C.I. Consultants Ltd
- Fluor Inc.
- UK Atomic Energy

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1. Tool Familiarisation

The aim of the User Manual is to familiarise the user with the CEQA tool and its functionalities. The manual is intended to cover all the areas regarding the quality assessment tool; areas on which a potential user may require some help and/or further clarifications.

The tool was developed using Microsoft's Excel for two reasons: Firstly, because almost everyone has Excel installed at their pc, and secondly, for reasons of simplicity. Although the tool itself is easy to use, and it functions are quite self-explanatory, every effort has been made to provide help on all the tool's aspects within this User Manual.

1.1 Before Starting

The navigation through the various Excel spreadsheets is aided with the use of some buttons. Although not essential, it is recommended that you enable the use of Macros within Excel. This can be done by clicking within Excel on **Tools/Macro/Security** and setting the security level to **Low**. All the calculations are carried out automatically on the background. The user is only requested to rate the 28 characteristics.

1.2 Button Commands

There are a number of buttons found within the tool aimed to help the user navigate through the various spreadsheets. Their functions are presented below:

Button Name	Found within Sheet:	Function
Start	*Introduction*	When pressed it will open the 'Estimate Assessment' sheet, so the user can start working with the tool
Estimate	*Estimate Assessment*	When pressed it will open the 'Estimated level of Confidence' sheet, where the result of the assessment is presented
Return to Ratings	*Estimated level of Confidence*	When pressed it will return the user to the 'Estimate Assessment' sheet

2. Notes Regarding the Rating Process

In order to find out how good the quality of an estimate/model is, based on the 28 identified criteria, the user has to rate each one of them against that particular estimate/model. Each characteristic in the tool has a drop-down menu where the user should select one of the five possible options. These options are listed below:

Rating	Equivalent to:	Comments
N/A	Not Applicable	Would exclude this characteristic from the tool's calculations
0	Not at all	Minimum value of the rating scale
1	Partially	*as per description*
2	Satisfactory	*as per description*
3	More than Satisfactory	*as per description*
4	Excellent	Maximum value of the rating scale

The options 0 to 4 found within each drop-down menu correspond to a scale, representing how satisfactorily this characteristic is met. The rating of 0 corresponds to the lowest possible score for that characteristic (where it hasn't been addressed, for example), and the value of 4 corresponds to the maximum possible score for that characteristic (fully addressed).

The N/A option should <u>only</u> be used if the relevant characteristic is not applicable to the actual model/estimate that is assessed. It is recommended that, if possible, all characteristics are rated, as all of them have been identified as being important towards achieving a good estimate. Use the N/A option only if one of the questions is completely irrelevant to your estimating needs/situation.

3. Rating of Characteristics - Additional Information

This section aims to provide additional explanations to the questions asked within the tool. The author recognises that the tool is targeted towards a wide audience with varying needs, and due to the tool's generic nature the author believes that additional explanations should be provided in order for the user to be able to relate what is asked in the tool to their own situation. Note that the numbering and sequence of the questions in Table 1, are exactly the same as found within the tool.

Table 1 – Additional Clarifications Regarding the 28 Rating Characteristics

#	Question	Explanation (if applicable)
	Estimate Purpose & Conditions	
1	Was the estimate based on a clearly defined scope of work?	Whether a well defined Scope of Work has been provided, in advance, to the cost estimator
2	Does the estimate appear to be updated for economic period?	Whether any rates were used to update the estimate for economic period (inflation rates etc)
3	Are the manufacturing quantity and productions rate(s) included with the estimate?	Whether any information were provided to the estimator as per the production quantity and the magnitude of the intended production/work
	Estimate	
4	Are the results of the estimate presented in a simple and clear manner?	How clear are the results presented, and whether there is enough visibility
5	Does it appear that the estimate is based in a high level of technical detail?	How good is the level of technical detail (on which the estimate was based on), compared to the type of estimate developed and the effort spent
6	Has a pre-defined process been followed in order to carry out the estimate (such as department procedures)?	Whether the development of the estimate was based on a pre-defined process (fore example, following department procedures, if any)
7	Has the estimate/model been calibrated to the company's processes/rates?	*Self-explanatory*
8	Is there a Basis of Estimate (BOE) provided with the estimate?	*Self-explanatory*
9	Does the estimate summarize the main cost elements involved (eg. Breakdown into labour, materials, sub-contractor involvement etc)?	Whether within the estimate/model, main categories are individually reported; e.g. costs are separately estimated for labour, materials and not as a whole lump sum
10	How complete/defined is the estimate's WBS/PBS/CBS for the type of estimate that is carried out for? (according to its purpose)	Based on the technique used, and purpose of the estimate, how complete/defined is the estimate's breakdown structure
	Documentation	
11	Have the rules and assumptions made been documented?	Either attached to the estimate, or documented within the estimate report
12	Have the data sources used been documented?	Whether the sources have been documented; having a trail of evidence (e.g. people interviewed, databases used and so on)
13	Has a report/documentation been submitted with the estimate, covering every aspect of it?	*Self-explanatory*
	Data & Knowledge Utilised	
14	Has the estimate been based on valid quotes for purchased content?	(only applicable in the case whether there is a sub-contractor element involved)
15	Are the data & the information sources used considered to be credible and reliable (whether the sources are experts or databases/ documents)?	Whether 'you' trust the data & information sources. How trustworthy are the people who provided you the inputs, or how credible do you believe the databases/documents you used are.

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16	Have other areas/departments of the business contributed to the estimate (such as inputs from Finance dpt, Operations etc)?	That could be in terms of knowledge provided, provision of rates, engineering data, and so on
	Risk Identification	
17	Has an evaluation of potential risks taken place and the corresponding risks identified?	Whether the risks associated to that estimate have (at least) been captured and evaluated, as a minimum.
	Miscellaneous	
18	Have the cost drivers been identified (e.g. for cost reduction purposes)?	Whether the cost estimator has identified the main cost drivers, areas of concern, areas for cost reductions and/or negotiations, and so on
19	Was the estimate delivered on time?	*Self-explanatory*
20	Do you think the choice of cost estimating method and the effort spent on the estimate is appropriate to its final use?	*Self-explanatory*
21	Is there a relationship to schedule, shown within the estimate?	Whether there are clear references within the cost estimate to the programme schedule. Could be the way major milestones are captured, and costs are estimated against such a time-profile
	Estimate Validation	
22	Has the estimate been reviewed by peers?	Whether another colleague has already reviewed the estimate/model; or there was another form of assessment, such as a board review
23	Has the supplier (or other interested parties) bought-in the process/model?	Interested parties could be any client, sub-contractors, area manager, and so on
24	Have the assumptions made been validated by a subject matter expert?	Whether the assumptions have been reviewed and approved (to be logic and correct) by anyone with an expertise in the corresponding area
25	Is the estimate accurate (specific to the type of estimate/business need)?	How accurate was the estimate/model towards the final incurred cost, taking into account the purpose & type of the estimate. Some times it will be impossible to know, so the N/A option should be selected
26	Has the estimated cost been benchmarked against industry norms (like carrying out a market study of similar products)?	Whether a market survey has taken place to compare the total cost of the project/system/part against norms around the industry; or even the cost of individual elements of that estimate/model
27	Have any additional cost estimating techniques been employed to cross check; or has the estimate's output been checked against an existing calibrated/proven cost model?	Whether the estimator used another technique to cross-check the accuracy of his estimate/model (e.g. Carrying out a simple analogy, before proceeding to a more detailed estimate). Another instance would be to cross check with using an already proven model (being COTS or not).
28	Is it possible to check the estimate, or part of it, against a known cost (for example, a past 'similar to' estimate)?	Whether the results of the estimate/model, or just parts of it, could be checked against some past estimates of similar products. 4 would mean that most of the estimate/model's elements could be checked, while 0 would mean none of the elements of the estimate/model have been checked against 'similar to', past, costs.

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